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A COMPARISON OF OBJECTIVE HURRICANE FORECASTING METHODS AND ATTEMPTS TO COMBINE TWO OR MORE OF THESE METHODS

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FOREWORD

This work was produced under Task 12, Tropical Forecasting Techniques, and contains a description of several methods for forecasting the movement of tropical storms. Statistical comparisons are made between these objective forecasting methods, or combinations using several forecasting techniques, and the official forecasts of tropical storm movement.

The Navy Weather Research Facility will continue to evaluate the objective methods described in this report as new data, using all of these techniques, become available from actual forecasts made at the Fleet Weather Facility, Miami (Jacksonville after 1 December 1964).

This report was written by Mr. Harold A. Corzine, Task Leader of Task 12, and was edited by Mr. René V. Cormier, Assistant Editor, and Mr. John M. Mercer, Editor, for the Navy Weather Research Facility.

This publication has been reviewed and approved on 30 November 1964 by the undersigned.

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INTRODUCTION

During the past few years several objective techniques have been developed for the purpose of predicting the movement of tropical cyclones. As these techniques have become available they have been employed by the forecasters at the Fleet Weather Facility (FWF), Miami (and others) and the results, whenever possible, have been considered in preparing the official forecasts issued by that facility.* An evaluation of these various techniques at the end of the past several seasons has indicated that *frequently* the objective techniques would have produced better forecasts than those issued in the official warning. However, no single objective forecasting system has, to date, proven to be *consistently* reliable.

The purpose of this study was to investigate the feasibility of combining the forecasts obtained by these different methods into a *single, objective* 24-hour forecast, which would consistently predict the storm movement more accurately than the more subjective official forecast.

**To be Fleet Weather Facility, Jacksonville after 1 December 1964.*

1. PREDICTORS AND DATA

1.1 Possible Predictors

Four objective and two semiobjective forecast techniques are presently being applied on a regular basis at FWF, Miami to obtain forecasts of 24-hour storm movement. A more detailed discussion of these techniques are included in the appendices, but they are briefly summarized in the following paragraphs.

1.1.1 Arowa (Riehl-Haggard Grid) Method

This method employs an objective technique by which the meridional and zonal components of hurricane motion are predicted using the 500-mb. steering current in the area closely surrounding the storm (appendix A).

1.1.2 Miller-Moore Method

This method is very similar to the AROWA method with the exception that steering at the 700-mb. level is employed instead of at the 500-mb. level. In addition, 12-hour persistence is also considered (appendix B).

1.1.3 Travelers 1960 Method

The Travelers method is an objective technique which uses the sea level synoptic chart and persistence as its primary tools, although some upper-air data is used in northern latitudes (appendix C).

1.1.4 Numerical Weather Prediction (NWP) Method

Numerical prediction uses an objective technique by which the future storm track is determined by solving the barotropic equation of motion at 500 mb., using electronic computer methods.

1.1.5 Extrapolation Method

Extrapolation is a semiobjective technique by which the past track is extended using current values of speed, direction, and intensity, with changes to these current values being applied as indicated by a continuous plot of extrapolation tendencies.

1.1.6 Climatology Method

Climatology uses a semiobjective technique where forecasts of future movement are obtained by considering average climatological storm tracks together with average climatological movement vectors (speed and direction) applicable to the storm's present position and past track.

Those methods using upper-level steering have one major disadvantage which should be noted. Forecasts made by these techniques are usually not available until 4 or more hours after observation time and cannot be used in the advisories until 10 of the 24 hours of the forecast period have elapsed. As a consequence, any combination of techniques which contains one or more of these methods will have the same limitation.

1.2 Data

The forecast data used was furnished by FWF, Miami. Initially only 2 years of forecast information were available, 1961 and 1962. During those 2 years 320 numbered warnings were issued. Inspection of this sample revealed that the number of cases where forecasts by all six methods had been concurrently made was inadequate for the planned investigation. However, if one forecast technique (NWP) were eliminated, the sample size could be increased by nearly 70 percent. Therefore, that technique, for this present investigation, was excluded from consideration. Discarding the NWP forecasts provided a sample of 111 cases where concurrent forecasts by the remaining five techniques were available for comparison. These included forecasts issued on tropical storms [1] as well as hurricanes, since limiting the data to only storms of hurricane intensity would again have resulted in too small a sample.

Additional forecast periods were added to the original 111 cases by processing the 1959 and 1960 hurricane season data. This was accomplished through the cooperative efforts of FWF, Miami and NWRF personnel. Using operational surface and upper-air charts from FWF files, Travelers, Miller-Moore, and AROWA forecasts were obtained for all possible cases. No attempts were made to make forecasts with the less objective, extrapolation and climatology, methods for fear that knowledge of the storm's future position might lead to the inclusion of

[1] A tropical storm is a closed cyclonic system of tropical origin with wind speed between 34 knots and 65 knots. A hurricane has wind speeds of 65 knots or higher.

bias in the forecasts. Out of 243 warnings issued during this second 2-year period, only 62 cases met the criteria for the computation of the desired forecasts.

No attempt was made to use hurricane data prior to 1959 because those data years were included in the development of one or more of the empirical techniques being used as predictors in this study. Thus, the data sample used in this investigation consists of 173 (111 + 62) of the 563 warnings issued during the 4-year period, 1959-62.

The storm data are contained in two sets of data sheets entitled (1) Tropical Cyclone Warning and Verification Data and (2) Objective Forecasting Techniques Verification and Data. Examples of the data sheets are included in appendix D. The first form includes the storm serial number (that is, the year and the storm number for that year), warning number, date and time of the warning (normally issued at 0400Z, 1000Z, 1600Z, and 2200Z), the present position, best track position, present course and speed, and the official, the extrapolation, and the climatology forecasts. The second form contains the storm serial number, the date and time of the synoptic chart which is used to make the forecast, the present and the best track positions at synoptic time, and the Travelers, Miller-Moore, and AROWA forecasts.

Although forecasts for 12, 24, and 36 hours and in some cases longer periods are included on these sheets, only the 24-hour forecast was investigated. The 12-hour forecast period is too short to warrant investigation, and at this time there is not a sufficient number of forecasts for periods greater than 24 hours available for study.

The term *present position,* as used in this report, is the assumed position of the storm's eye at the beginning of the forecast period, based on all the data available to the forecaster at that time. The *best track position,* on the other hand, is determined by post-analyses and is based on all available data concerning the storm, such as reconnaissance fixes, land station radar fixes, special aircraft and ship reports, surface maps, and upper-air reports and analyses.

2. PROCEDURE

2.1 General Discussion

Ideally, a homogeneous set of data should be used, in which only those forecasts which were made at the same initial times by each method are compared. However, this was impossible with the existing data. The official, the extrapolation, and the climatology forecasts are made at warning times which are 4 hours after synoptic time and which verify 24 hours later. The objective forecasts, however, verify 24 hours after the synoptic time of the charts upon which they are based. In order to make these forecasts comparable, certain assumptions had to be made. First, it was assumed that it is operationally feasible (under ideal conditions) to have the *objective* forecasts ready 4 hours after synoptic time; these could then be compared with the three other forecasts made at this (the warning) time. Second, it was assumed that during this 4-hour period the surface and upper-air flow patterns did not change significantly with respect to the storm, even though the storm itself was moving. If these assumptions were to be accepted the 24-hour components of movement, forecast by the objective methods, could be applied to the present position at warning time, to obtain a forecast position comparable with the official forecast and semiobjective techniques.

However, as it stands now these assumptions cannot be religiously accepted, especially the first one. For this reason, this investigation will be primarily to study the feasibility of the approach rather than to develop equations for operational use. It is hoped that research reported in this publication will result in an improved forecasting approach which may, at a later date, be applied to *longer term* forecasts for operational use.

2.2 The Predictand

The predictand, the observed component of movement (either latitudinal or longitudinal) which we are attempting to forecast, requires some definition. Ideally, this variable should be found by taking the difference between the present best track position (latitude or longitude) and the best track position 24 hours later. However, to do so would assume knowledge not available to the forecaster at forecast time, since the *present best track position* (based on a post analysis using data from all different sources) is not known at that time. Instead, the *present position* (assumed position) is considered as the initial position at forecast time and the observed movement is the difference between this position and the best track position at the end of the forecast period. Usually the difference between the *present position* and the *best track position* is small, but under certain conditions the difference can be significant. For example, storms in areas outside the range of aircraft reconnaissance are difficult to locate accurately; also the centers of storms with large and ill defined eyes are difficult to locate. *Ella* (1962) was a good example of this. To check the magnitudes involved, the errors in the position of the storms were calculated for the 173 cases used in this study. The average vector error magnitude was 25 nautical miles with a range of 0 to 120 miles; 62 percent of the time the errors were less than the average. It is difficult to determine the percentage of errors in the subsequent forecasts due to the initial positioning errors. Nevertheless, an experiment for just this purpose was conducted by Tracy of the National Hurricane Research Project [3]. He used the Travelers technique, since it is the method generally accepted as being, on the average, the most accurate of all existing objective techniques. He found (using 37 forecasts) that if the initial and persistence storm positions, determined operationally, were used to make the forecast the average forecast vector error was 90 nautical miles. If, however, the best track positions were used the average forecast vector error was 73 nautical miles. Thus, it appears that a significant part of the forecast error may well be a result of the improper positioning of the storm rather than a weakness of the forecast techniques themselves.

2.3 The Predictors

The predictors, the forecast components of movement (latitude and longitude), were obtained by finding the difference between the present position at warning time and the position forecast 24 hours later in the case of extrapolation and climatology. In the case of the objective techniques, the forecast movement is the difference between the 24-hour forecast position and the present position at synoptic time. The forecasts are compared and combined by using extrapolation and climatology forecasts at warning time and the objective forecasts made at the synoptic time which just precedes the warning time.

2.4 The Computer Program

Using a Bendix G-15 computer, this data was processed on a correlation and regression program known as *CARP II*. This program is designed to compute the coefficients of a multiple regression equation expressing the dependent variable Y as a function of the five independent variables $X_1, X_2, \ldots X_5$. The regression equation is of the form

$$Y = A_1X_1 + A_2X_2 + \ldots + A_5X_5 + B ,$$

where the A's and B are constants determined by the program and in this work are referred to as weighting factors. A more complete discussion of the program is presented in appendix E.

Using this approach, three groups of regression equations were developed. Group I consists of two equations developed to forecast the 24-hour change in (1) latitude and (2) longitude of the position of a storm based on the entire 173 cases with no attempts at stratifying the data. In groups II and III the storms have been stratified by geographic location and past movement, respectively. The stratification methods employed resulted in a total of seven classes, three in group II and four in group III. As in group I, 2 equations, one predicting latitude movement and the other longitude movement, have been developed for each of the seven classes resulting in a total of 14 regression equations for groups II and III. Thus, 16 equations have been developed for the three groups.

2.5 The Prediction Equations

In the following equations all displacements (ϕ-latitude, λ-longitude) are for 24 hours in terms of degrees of latitude. The subscripts to the predictors in every case are defined as follows:

1. Extrapolation
2. Climatology
3. Travelers
4. Miller-Moore
5. AROWA

i.e., $\Delta\phi_3$ refers to the latitudinal displacement obtained from the Travelers method.

2.5.1 Group I

Equations 2.1 and 2.2 consist of unstratified data, and are applicable for all Atlantic, Gulf of Mexico, and Caribbean tropical cyclones (see table 2.1).

2.5.2 Group II

Equations 2.3 through 2.8 are the equations for the data stratified by geographic location; that is, regions (see table 2.1). The areal limits used in defining the regions are similar to those originally outlined by Tracy [3], with some modification for ease in sorting the data by machine (fig. 2.1). These areas were selected because they roughly delineate the areas of data density with the most data usually available in region B, followed by region C, with the least available data in region A.

(a) Region A

Equations 2.3 and 2.4 are applicable for all storms located east of 60° W. longitude regardless of latitude.

(b) Region B

Equations 2.5 and 2.6 are applicable for all storms at or west of 60° W. longitude and south of 30° N. latitude.

(c) Region C

Equations 2.7 and 2.8 are applicable for all storms at or west of 60° W. longitude and at or north of 30° N. latitude.

2.5.3 Group III

Equations 2.9 through 2.16 were developed using the data stratified by the direction of storm movement during the 12-hour period just prior to forecast time (see table 2.1). Figure 2.2 depicts an idealized hurricane track logically separated into W, X, Y, Z movement segments which are described below.

(a) Set W

Equations 2.9 and 2.10 include those storms whose past 12-hour movement was westward and and whose longitudinal (westward) movement was of greater magnitude than the latitudinal (northward) movement. This set, however, also includes storms moving westward through the southwest quadrant (bearing, 180° through 270°) *regardless* of the relative component speeds.

(b) Set X

Equations 2.11 and 2.12 like set W include

TABLE 2.1. Prediction Equations 2.1 through 2.16.

Group I (Unstratified.)

	$\Delta\phi = \cdot631\,(\Delta\phi)_3 + \cdot189\,(\Delta\phi)_5 + \cdot133\,(\Delta\phi)_2 - \cdot277$	(2.1)
	$\Delta\lambda = \cdot751\,(\Delta\lambda)_5 + \cdot266\,(\Delta\lambda)_3 + \cdot078\,(\Delta\lambda)_1 - \cdot133$	(2.2)

Group II (Stratified by geographic region.)

Region A	$\Delta\phi = 1\cdot072\,(\Delta\phi)_3 + \cdot120\,(\Delta\phi)_5 - \cdot828$	(2.3)
	$\Delta\lambda = 1\cdot148\,(\Delta\lambda)_3 + \cdot140\,(\Delta\lambda)_5 + \cdot034$	(2.4)
Region B	$\Delta\phi = \cdot449\,(\Delta\phi)_5 + \cdot411\,(\Delta\phi)_2 - \cdot328$	(2.5)
	$\Delta\lambda = \cdot609\,(\Delta\lambda)_5 + \cdot378\,(\Delta\lambda)_3 - \cdot037$	(2.6)
Region C	$\Delta\phi = \cdot574\,(\Delta\phi)_5 + \cdot162\,(\Delta\phi)_3 - \cdot330\,(\Delta\phi)_2 + 2\cdot672$	(2.7)
	$\Delta\lambda = \cdot603\,(\Delta\lambda)_5 + \cdot150\,(\Delta\lambda)_3 - \cdot769$	(2.8)

Group III (Stratified by direction of storm movement.)

Set W	$\Delta\phi = \cdot307\,(\Delta\phi)_5 + \cdot352\,(\Delta\phi)_3 + \cdot499$	(2.9)
	$\Delta\lambda = \cdot452\,(\Delta\lambda)_5 + \cdot350\,(\Delta\lambda)_2 + \cdot676$	(2.10)
Set X	$\Delta\phi = \cdot416\,(\Delta\phi)_5 + \cdot278\,(\Delta\phi)_3 + \cdot236$	(2.11)
	$\Delta\lambda = \cdot568\,(\Delta\lambda)_5 + \cdot269\,(\Delta\lambda)_3 - \cdot250\,(\Delta\lambda)_4 + \cdot804$	(2.12)
Set Y	$\Delta\phi = \cdot599\,(\Delta\phi)_3 + \cdot170\,(\Delta\phi)_5 + \cdot671$	(2.13)
	$\Delta\lambda = \cdot835\,(\Delta\lambda)_5 + \cdot169\,(\Delta\lambda)_3 + \cdot234$	(2.14)
Set Z	$\Delta\phi = \cdot989\,(\Delta\phi)_3 + \cdot220\,(\Delta\phi)_5 - \cdot106$	(2.15)
	$\Delta\lambda = 1\cdot158\,(\Delta\lambda)_3 + \cdot350\,(\Delta\lambda)_5 - \cdot163\,(\Delta\lambda)_1 + \cdot368$	(2.16)

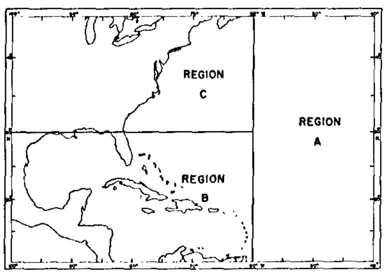

Figure 2.1. Regions in which Tropical Storms Were Located At Time of Forecast; Used for Geographic Classification (Group II).

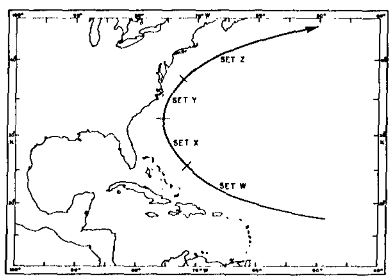

Figure 2·2. Idealized Hurricane Track Divided Into Four Segments by Direction of Movement, as Used for Group III Forecasts.

westward moving storms; however, here the longitudinal (westward) movement for the past 12 hours was equal to or less than the latitudinal (northward) movement.

(c) Set Y

Equations 2.13 and 2.14 include those storms whose past 12-hour movement was northward or eastward, and whose longitudinal (eastward) movement was less than the latitudinal (northward) movement.

(d) Set Z

Equations 2.15 and 2.16 include mainly those storms whose past 12-hour movement was eastward and whose longitudinal (eastward) movement was equal to or of greater magnitude than the latitudinal (northward) movement. This group also includes storms moving eastward through the southeast quadrant (bearing 90° through 180°) regardless of the relative component speeds.

2.6 The Modified Travelers Method

The Travelers objective forecast technique, since based primarily on surface pressure charts as opposed to upper-air charts, has two distinct advantages over the other two objective methods considered in this report. First, surface data is usually more abundant than upper-air data, thereby providing for a relatively better surface analysis; and second, this data is available earlier, thereby permitting its use for advisories 6 hours earlier than the other two methods. In addition, forecasts on storms south of 27.5° N. depend soley upon surface data, and this is available four times daily instead of twice daily as is the case of upper-air data. Storms north of 27.5° N. require some 500 mb. data which, therefore, places certain restrictions on the availability of these forecasts.

Because of the availability of a forecast by the Travelers method at official forecast time and its persistent high correlation with the observed movement, as evidenced by its frequent appearance in equations 2.1 through 2.16, an attempt was made to modify the existing Travelers method to improve its forecasting accuracy. The investigation of only one technique permitted the inclusion of an additional 85 cases (from the original 4-year period) to the data sample, thereby enlarging it to 258 cases. This sample size is of the same magnitude as the 279 cases used in the original development of the Travelers technique. Since the modified method consists of an entirely different set of forecasts, it would seem reasonable to assume that these should result in forecast movements at least as representative of the actual movement of a storm as are the results of the original Travelers equations.

In addition, the modified equations are probably more operationally applicable than the original equations, since (because of the approach used) the weighting factors not only compensate for any systematic error in the original forecast but also for the 4-hour period between the synoptic chart and warning time. Essentially, the modified equations produce a forecast based on synoptic data which verifies 24 hours after warning time instead of 24 hours after synoptic time. The result is, in reality, a 28-hour forecast.

Using the same procedure outlined in appendix E, equations 2.17 through 2.26 (table 2.2) were developed. The first two equations (2.17 and 2.18) are based on the entire data sample. The remaining eight equations (2.19 through 2.26) are based on a stratified sample utilizing the same movement stratification scheme used in group III.

TABLE 2.2. Prediction Equations 2.17 through 2.26.

	Travelers Modified (Unstratified.)	
	$\Delta\phi = \cdot 809\,(\Delta\phi)_3 + \cdot 2332$	*(2.17)*
	$\Delta\lambda = \cdot 901\,(\Delta\lambda)_3 + \cdot 2451$	*(2.18)*
	Travelers Modified (Stratified by direction of storm movement.)	
Set W	$\Delta\phi = \cdot 461\,(\Delta\phi)_3 + \cdot 8734$	*(2.19)*
	$\Delta\lambda = \cdot 862\,(\Delta\lambda)_3 + \cdot 5769$	*(2.20)*
Set X	$\Delta\phi = \cdot 640\,(\Delta\phi)_3 + \cdot 4939$	*(2.21)*
	$\Delta\lambda = \cdot 455\,(\Delta\lambda)_3 + \cdot 5505$	*(2.22)*
Set Y	$\Delta\phi = \cdot 807\,(\Delta\phi)_3 + \cdot 7644$	*(2.23)*
	$\Delta\lambda = \cdot 382\,(\Delta\lambda)_3 - \cdot 2573$	*(2.24)*
Set Z	$\Delta\phi = 1\cdot 172\,(\Delta\phi)_3 - \cdot 2073$	*(2.25)*
	$\Delta\lambda = 1\cdot 118\,(\Delta\lambda)_3 - \cdot 5455$	*(2.26)*

3. EVALUATION OF THE EQUATIONS

3.1 Groups I, II, and III

A total of 1,035 forecasts were constructed by the author (and aerographer's mates) using equations 2.1 through 2.26 and the dependent data; that is, the same data used to develop the equations. Appendix F presents the general form of the worksheet used to compute the forecast movements. The results of these forecasts were compared with the observed movement, and the resulting forecast errors were computed. Table 3.1 presents the average forecast error for the forecasting techniques previously described and the techniques developed in this study, and allows easy comparison of all of these techniques with the *official forecast*. Table 3.1 also shows the standard deviation of the average error, the total range of the errors, and the percentage of the time an objective forecast was better than the official forecast. All distances in this table are given in nautical miles. The first five forecast techniques (F_1 through F_5) are the predictors used in the regression equations to develop the last five techniques. The predictors taken individually have average errors of greater magnitude than the official forecast. However, as stated before, occasionally (up to 46% of the time) they are more accurate than the official forecast. A true comparison of the objective forecasts and official forecasts is impossible, however, because whenever possible the objective forecasts were considered when making the official forecast. The techniques (F_6 through F_8 , group I, II, and III, respectively) were derived by combining two or more of the first five methods in the manner discussed in appendix E. Each of these combina-

TABLE 3.1. Comparison of Forecasting Techniques With the Official Forecast.

	Forecast Technique		Average Forecast Error (nautical miles)	Standard Deviation (nautical miles)	Range of Errors (nautical miles)	Percent of Time Better Than Official Forecast
PREDICTORS	Extrapolation	F_1	163	121	5-660	36
	Climatology	F_2	200	134	19-586	32
	Travelers	F_3	153 / 150*	101 / 98*	17-576	45 / 48*
	Miller-Moore	F_4	161	112	8-590	46
	AROWA	F_5	164	101	13-507	43
	OFFICIAL FORECAST		146 / 143*	102 / 97*	8-614	—
REGRESSION EQUATIONS	Group I	F_6	135	83	8-368	55
	Group II	F_7	127	83	0-401	59
	Group III	F_8	121	80	6-442	61
	Modified Travelers Unstratified	F_9	152 / 145*	102 / 97*	13-482	45 / 48*
	Modified Travelers Stratified	F_{10}	138 / 134*	90 / 88*	6-455	54 / 54*

*85 additional cases in the data sample.

tions shows, in all respects, an improvement over the official forecast, with group III (movement stratification) indicating the best results.

Since no independent data was available, the significance of the 25 nautical mile reduction in average error (146 minus 121) by this method was tested *statistically*, and was found to be significant at the 5 percent level. Although this test does not prove that the objective method is absolutely better than the official, it does indicate an extremely high probability that, on the average, the objective forecast would better the official forecast on independent data as well.

The second best method, group II, with an average error of 127 nautical miles, is also significantly better than the official forecast according to the same statistical test, and at the same level of significance.

The frequency with which these methods (group III and II) beat the official forecast in the dependent sample (61 percent and 59 percent, respectively) is especially encouraging, since both methods are *objective* and thus can be prepared by any forecaster regardless of experience. Admittedly, these methods are dependent upon sea level and upper-air analyses but, for that matter, so is the official forecast since these charts are considered by the forecaster in the preparation of the official forecast.

3.2 The Modified Travelers Method

The last two forecast techniques in table 3.1, F_9 and F_{10}, are modifications of the original Travelers method, the first consisting of the single set of equations for the unstratified sample and the second consisting of the four sets of equations for the sample stratified by past movement, as mentioned previously. Two sets of values are presented for each of the modified Travelers methods. Those values to the left of the slant are based on the original 173 case samples used to obtain the results for all the other techniques and those to the right include the 85 additional cases briefly discussed before. The modified set without *stratification* failed to produce improvement over the original Travelers forecasts. Stratifying by past 12-hour movement resulted in substantial improvement over the original Travelers forecast (15 and 16 nautical miles) and, for the dependent data at least, showed some improvement over the official forecast (8 and 9 nautical miles). It is of considerable significance that these results were obtained by completely *objective* means. More important, however, is the fact that this technique can be applied at warning time, thus providing a single operational objective method which is, on the average, at least as accurate as the official forecast.

3.3 Breakdown of Average Errors within Groups II and III and within Travelers Modified Methods

A breakdown of the average errors for the classifications within groups II and II and for the modified Travelers method, stratified as in group III, is presented in table 3.2. The reduction in the average error in certain classes over that of the official forecast, especially for storms stratified by past movement, is extremely encouraging. However, the results presented in tables 3.1 and 3.2 must be viewed with certain reservations because of the relatively small size of the sample used in the development of the regression equations.

Two sets, X and Y in group III, are of special importance as these two sets include those hard to predict storms undergoing recurvature off the east coast of the United States. The 36 nautical mile reduction in the average error in set X (25 percent of the total error) over the official forecast error, if deemed truly representative of the potential of the regression equations, is significant and should warrant further investigations of this type for longer forecast periods.

Set Z includes those fast eastward-moving storms, under the influence of the westerlies, which seldom are a hazard to any large landmass but which can be a major problem for shipping. The errors are large because of the direct relationship which exists between the speed of the storm and forecast errors; i. e., as storm speed increases, forecast error increases. The reduction in forecast error (45 nautical miles) using the regression equations is, nonetheless, substantial; representing 20 percent of the 223-nautical-mile official forecast error.

Set W, in addition to having a smaller error than the official forecast, has the smallest average error (88 nautical miles) of all the derived techniques. This class includes those storms undergoing little change in speed or direction and, in addition, is located in the region best covered by reconnaissance aircraft. The ability to improve on forecasts made under these optimum conditions is encouraging.

Classes *A*, *B* and *C* of the regional stratification all show some improvement over the official forecast (10, 15, and 36 nautical miles, respectively). The fact that class *A* produces the least improvement is not surprising, since surface and upper-level analyses, needed to make the objective forecasts, are of questionable quality in this region.

Although the average errors using the movement stratification and regional stratification are nearly equal, the movement stratification is preferred since, within a given region, storms may move in any direction, even though a particular direction of movement prevails. For example, in region *B* where the predominant movement is westerly, east to northeastward movement is not uncommon, especially late in the hurricane season. Another good example, region *A*, includes not only storms in their early stages moving westward at low latitudes but also eastward moving storms at high latitudes after they have recurved. If, for example, in these regions the forecast techniques persistently overforecast the westward movement and underforecast the eastward movement, a single equation for both movements would not compensate for this bias and would be unsuitable. Stratification by direction of movement, however, allows for compensation by means of the appropriate weighting factors.

For these reasons, only the stratification by past movement was applied when modifying the Travelers method. These results are also included in table 3.2. In the two classes, *X* and *Z*, the forecast error (127/131 and 191/194, respectively) was less than the official forecast error (145/152 and 223/220, respectively) while in the other two classes, (*W* and *Y*), the errors were nearly equal.

3.4 Distribution of Errors for Each Forecast Technique

In addition to the mean vector errors, the distribution of errors was investigated for each forecast technique. The results are presented in table 3.3. Even though the results are not outstanding, some reduction in error is noted. In group III 72 percent of the forecast errors are less than 150 nautical miles, as opposed to 180 nautical miles for this same percentage in the official forecast warnings; only 60 percent of the official forecast errors are less than 150 nautical miles. Twenty-two percent of the forecasts for storms stratified by past movement and seventeen percent of the official forecasts fall in the error range from 0 to less than 60 nautical miles. This range contains the largest single percentage increase, within a range (5 percent), over the official forecast error.

3.5 Component Errors

As a final step, the latitudinal and longi-

TABLE 3.2. *Comparison of Forecast Techniques, by Region or Set, with the Official Forecast.*

	EQUATIONS 2.3 THROUGH 2.16							*MODIFIED TRAVELERS EQUATIONS STRATIFIED BY MOVEMENT*							
	GROUP II			*GROUP III*				*ORIGINAL DATA SAMPLE (173 CASES)*				*ENLARGED DATA SAMPLE (258 CASES)*			
Region (A, B, C) or Set (W, X, Y, Z) (No. Cases)	*A* (34)	*B* (100)	*C* (39)	*W* (77)	*X* (34)	*Y* (30)	*Z* (32)	*W* (77)	*X* (34)	*Y* (30)	*Z* (32)	*W* (130)	*X* (54)	*Y* (37)	*Z* (37)
Average Error Using Techniques (nautical miles)	154	106	160	88	109	157	178	104	127	181	191	104	131	182	194
Average Error Using Official Forecast (nautical miles)	164	121	196	103	145	179	223	103	145	179	223	107	152	182	220
Percent of Time Better Than Official Forecast	47	60	67	57	65	67	63	52	65	43	56	52	63	46	54

tudinal components of movement were investigated separately. The mean component errors and their standard deviations were calculated and are shown in table 3.4. In addition, scatter diagrams showing forecast movement versus forecast error (forecast movement minus observed movement) for both latitude and longitude are included in figures 3.1 and 3.2. In each case the x-axis is the forecast movement and the y-axis is the forecast error. Perfect forecasts are indicated by points falling on the horizontal line marked zero, and the percentage of the forecasts with component errors falling in the ranges of ± 0.5°, ± 1.0°, and ± 2.0° of latitude are indicated on the right side of the figures. A positive latitude (longitude) forecast indicates northward (westward) movement, and a positive error denotes that the forecast movement was more northward (westward) or less southward (eastward) than was observed.

TABLE 3.3. *Percentage Frequency Distribution of Errors; Percent of Total/(Cumulative Percent of Total).*

	Range (nautical miles)					
Forecast Method	*0-59 (0-59)*	*60-89 (0-89)*	*90-119 (0-119)*	*120-149 (0-149)*	*150-179 (0-179)*	*>179 (0 to >179)*
Official Forecast	17 (17)	14 (31)	19 (50)	10 (60)	12 (72)	28 (100)
Group I	17 (17)	17 (34)	18 (52)	14 (66)	12 (78)	22 (100)
Group II	21 (21)	18 (39)	15 (54)	17 (71)	6 (77)	23 (100)
Group III	22 (22)	16 (38)	20 (58)	14 (72)	10 (82)	18 (100)
Modified Travelers (Unstratified)	17 (17)	12 (29)	20 (49)	8 (57)	11 (68)	32 (100)
Modified Travelers Stratified	19 (19)	15 (34)	17 (51)	13 (64)	7 (71)	29 (100)

TABLE 3.4. **Component Forecast Errors.**

	Latitude		*Longitude*	
Forecast Method	*Mean Error*	*Standard Deviation*	*Mean Error*	*Standard Deviation*
Official Forecast	92	78	95	90
Group I	83	72	92	72
Group II	78	72	84	72
Group III	81	66	74	66
Modified Travelers Unstratified	86	72	109	90
Modified Travelers Stratified	84	72	94	78
*Official Forecast**	91	78	92	84
*Modified Travelers * Unstratified*	86	72	99	84
*Modified Travelers * Stratified*	83	72	89	72

* Last three blocks have 258 cases, as opposed to 173 for other entries.

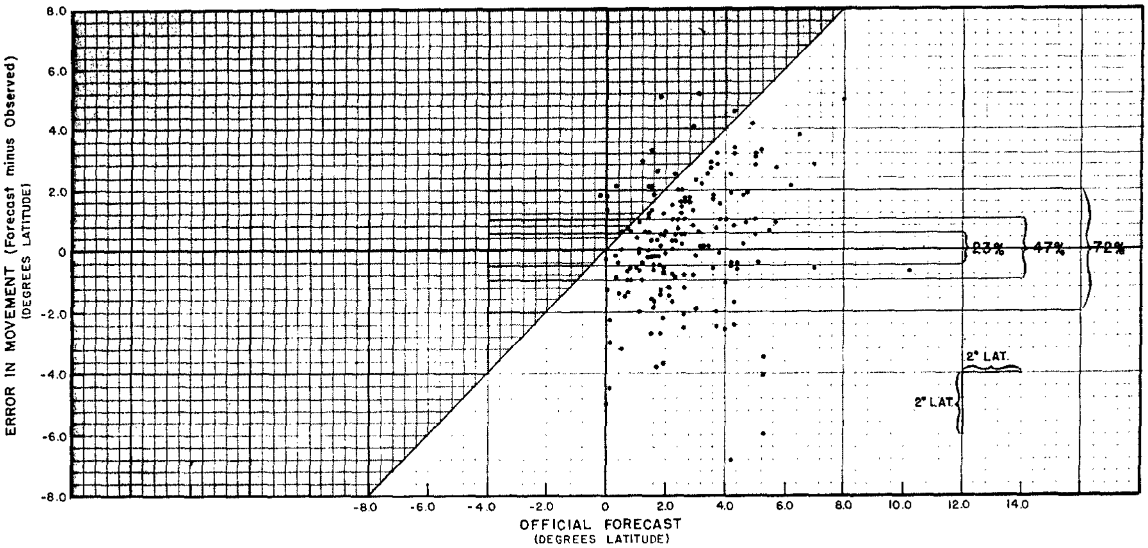

Figure 3·1a. 24-Hour Forecast (Meridional Component) Error Distribution; Official Forecast Versus Forecast Error.

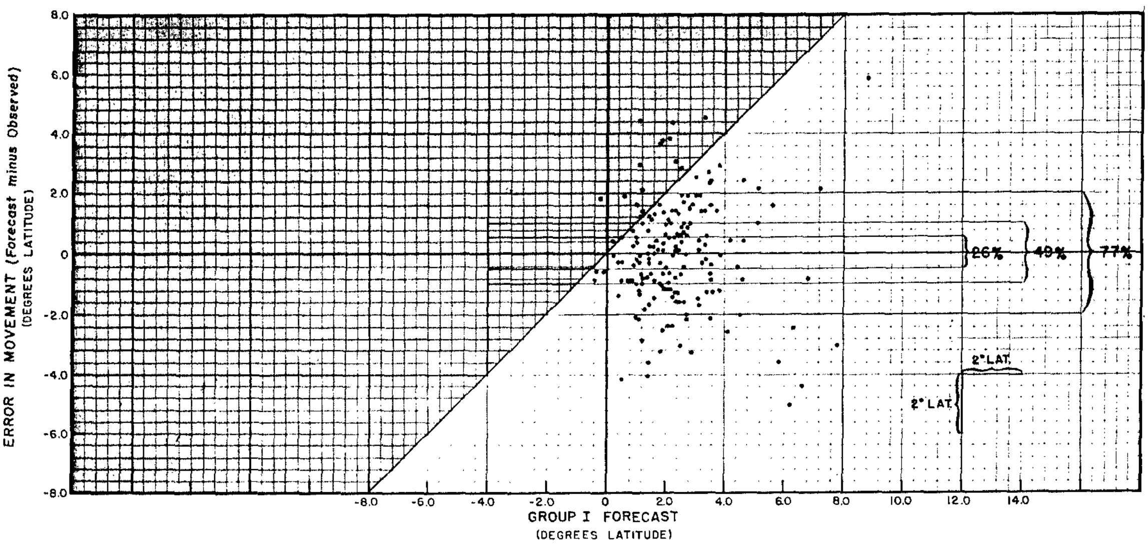

Figure 3.1b. 24-Hour Forecast (Meridional Component) Error Distribution; Group I Forecast Versus Forecast Error.

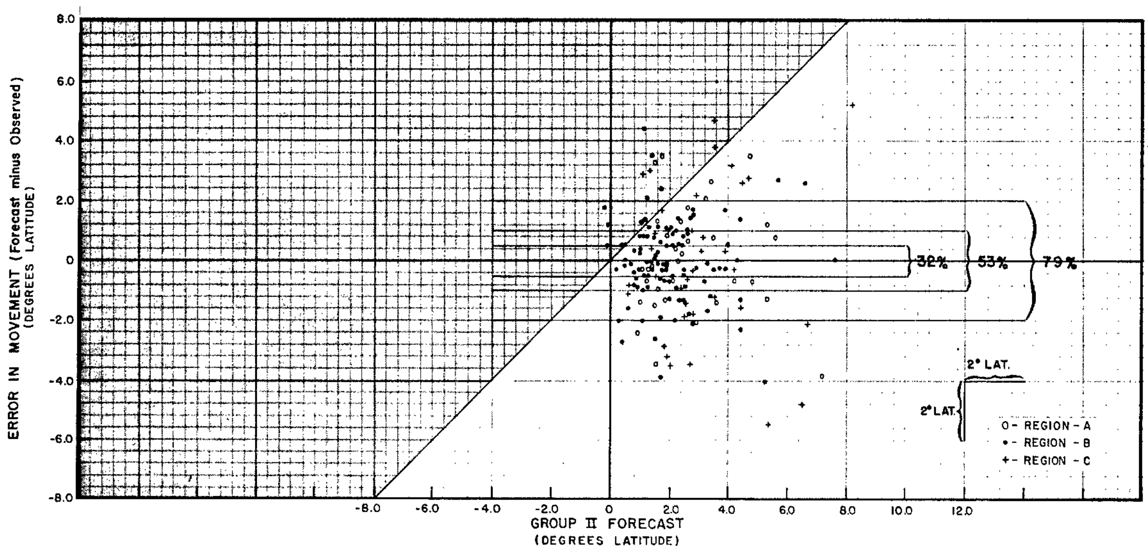

Figure 3.1c. 24-Hour Forecast (Meridional Component) Error Distribution; Group II Forecast Versus Forecast Error.

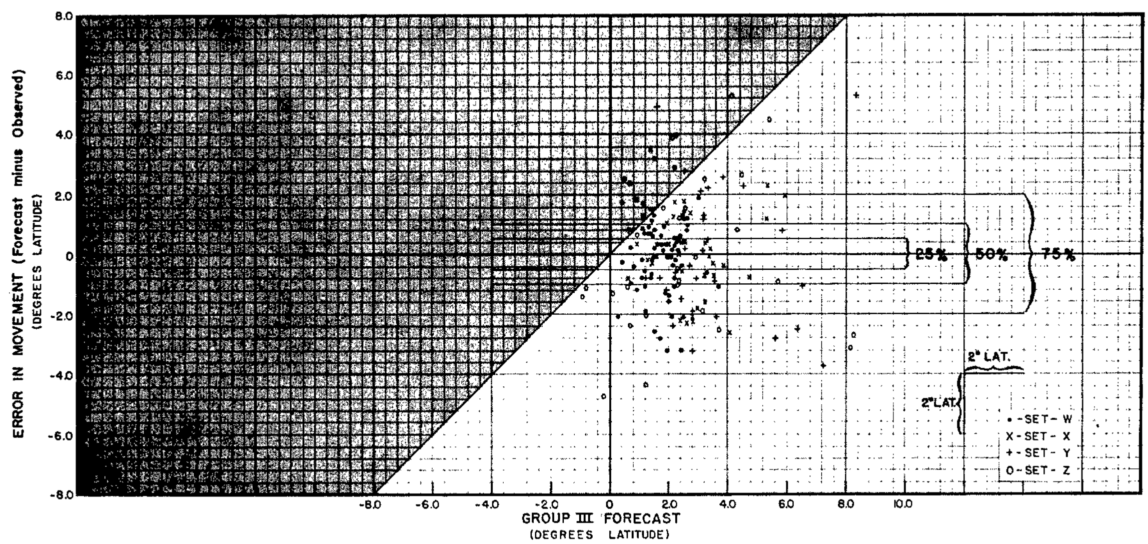

Figure 3.1d. 24-Hour Forecast (Meridional Component) Error Distribution; Group III Forecast Versus Forecast Error.

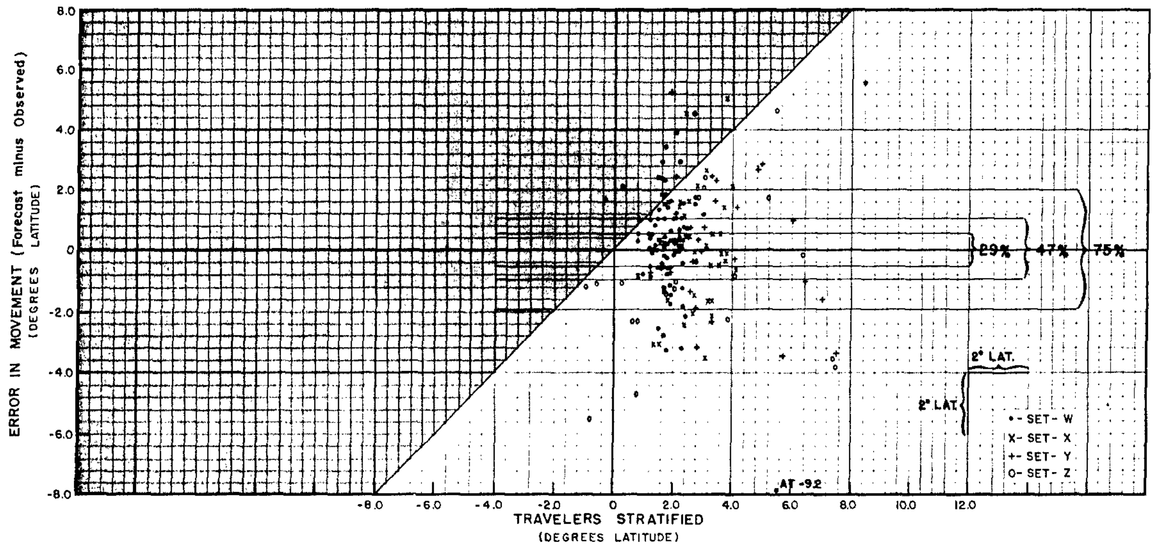

Figure 3-1e. 24-Hour Forecast (Meridional Component) Error Distribution; Modified Travelers (Stratified) Forecast Versus Forecast Error.

3.5.1 Latitude

The first five graphs (figs. 3.1a through 3.1e) present the meridional (latitudinal) movements by the techniques under discussion. One significant feature of every technique, including the official forecast, is the reluctance to forecast southerly movement. Sixteen cases of southerly movement were observed (shaded areas to the left of the diagonal) and none of those were predicted accurately. Only the group II predictions even indicated the correct direction in more than one case. On rare occasions the technique forecast southward movement, when the observed movement was northward (those cases of negative forecast to the right of the diagonal).

All methods had a greater number of errors in the smallest error range (± 0.5°) than the official forecast with the best results produced by the group II method. Twenty-three percent of the official forecast errors were less than ± 0.5° as compared to 32, 29, 26, and 25 percent by the group II, modified Travelers, group I, and group III forecasts, respectively. In addition, the number of forecast errors falling outside the ±2.0° range was reduced by all methods. Group II again gave the best results with only 21 percent of its errors greater than ± 2.0° latitude as compared to 28 percent by the official forecast.

3.5.2 Longitude

Comparisons of the zonal (longitudinal) component of movement are shown in figures 3.2a through 3.2e. Unlike the meridional forecasts only one technique, group III, shows any real improvement over the official forecast. Thirty-six percent of the group III longitudinal component forecasts have errors in the range ± 0.5°, whereas only 25 percent of the official forecasts fall in that range. Group III forecast errors exceeded ± 2.0° latitude only 17 percent of the time as compared to 23 percent for the official forecast.

3.6 Possibility of Combining Two Techniques

From the table of average component errors (table 3.4) and from the above figures (figs. 3.1 and 3.2) it appeared that it might be possible to further reduce the vector error by using a combination of two techniques, the regional stratification method (group II) for latitude movement and the past movement stratification (group III) method for longitude movement. A test of that possibility was conducted using existing data. The resulting average vector error was 116 nautical miles, a 5-mile reduction in the average error of the previous best forecast technique and a 30 nautical mile reduction in the average official forecast error.

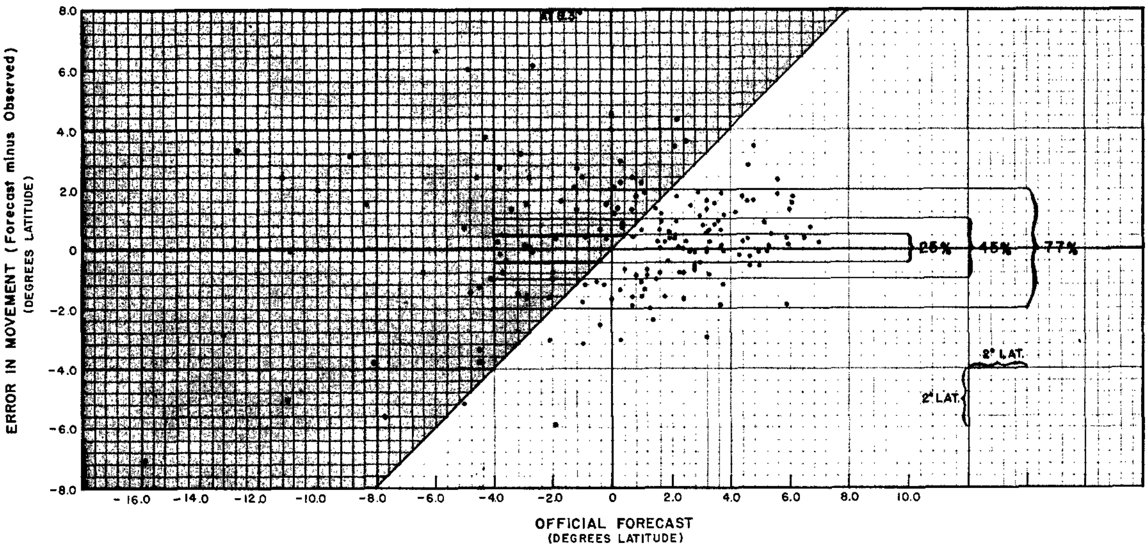

Figure 3.2a. 24-Hour Forecast (Zonal Component) Error Distribution; Official Forecast Versus Forecast Error.

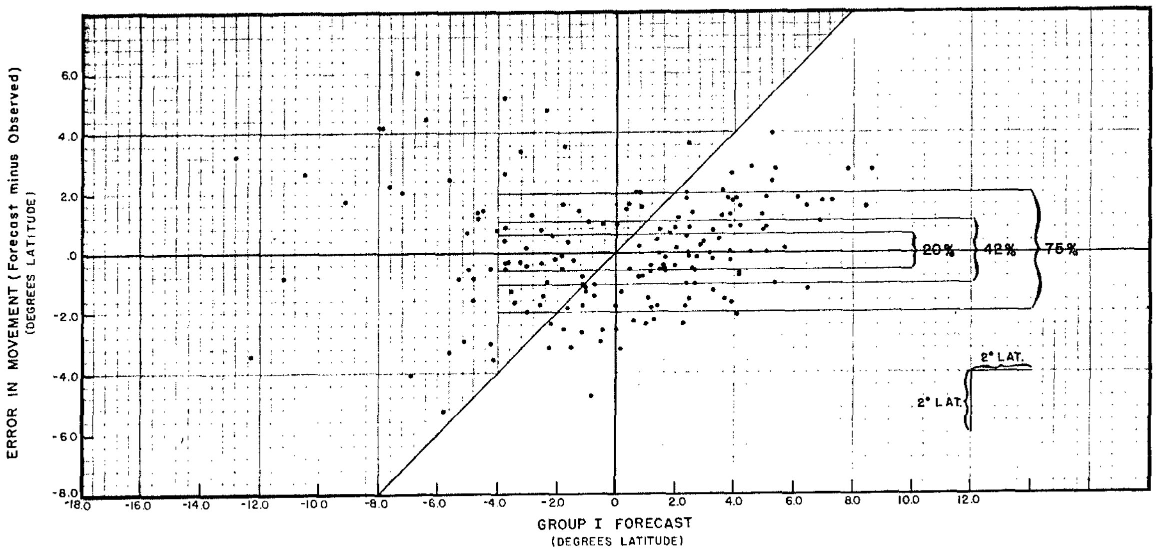

Figure 3-2b. 24-Hour Forecast (Zonal Component) Error Distribution; Group I Forecast Versus Forecast Error.

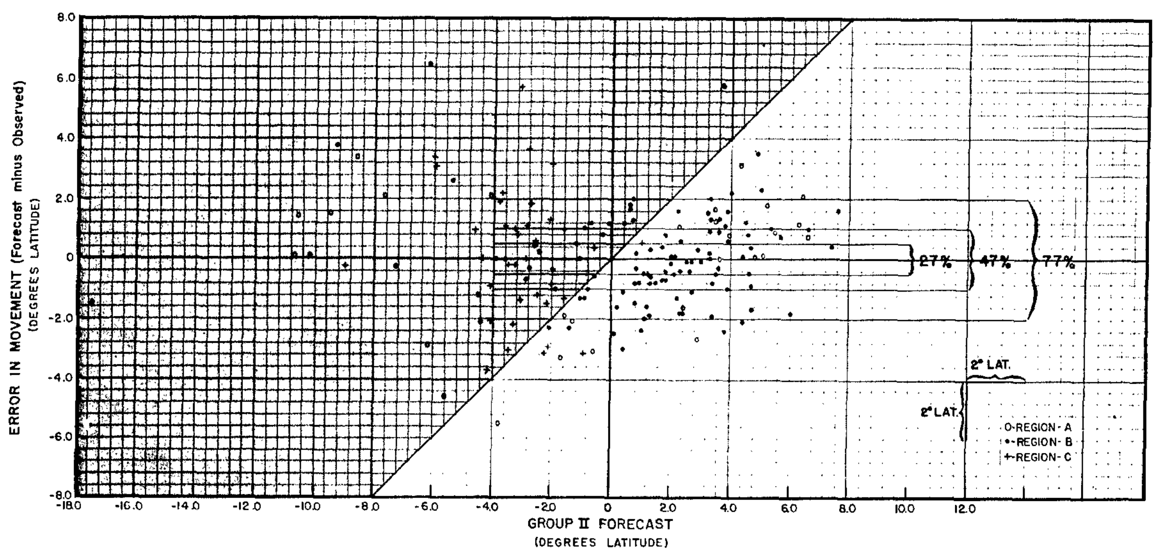

Figure 3-2c. 24-Hour Forecast (Zonal Component) Error Distribution; Group II Forecast Versus Forecast Error.

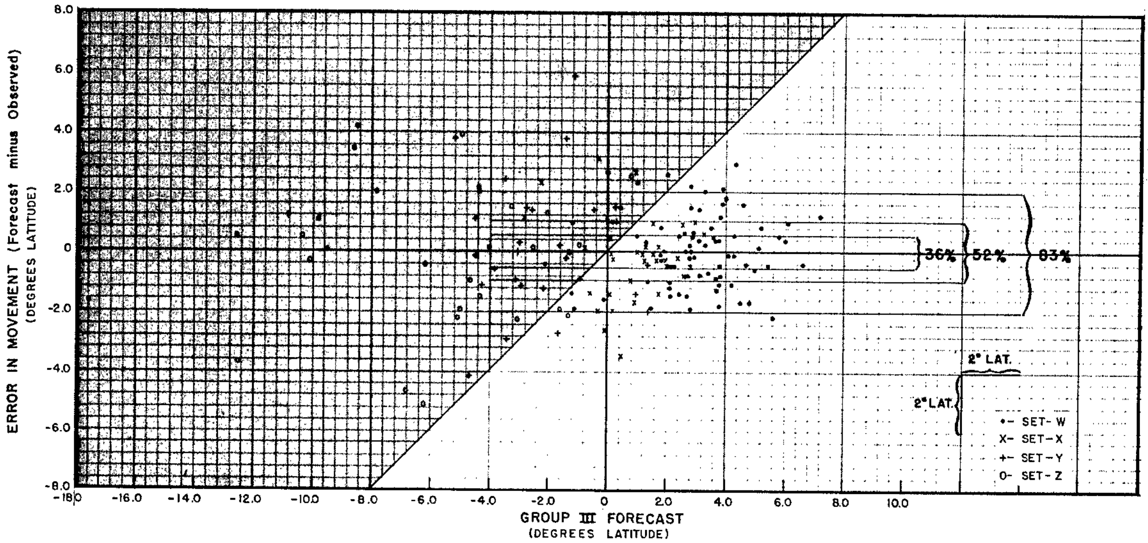

Figure 3.2d. 24-Hour Forecast (Zonal Component) Error Distribution; Group III Forecast Versus Forecast Error.

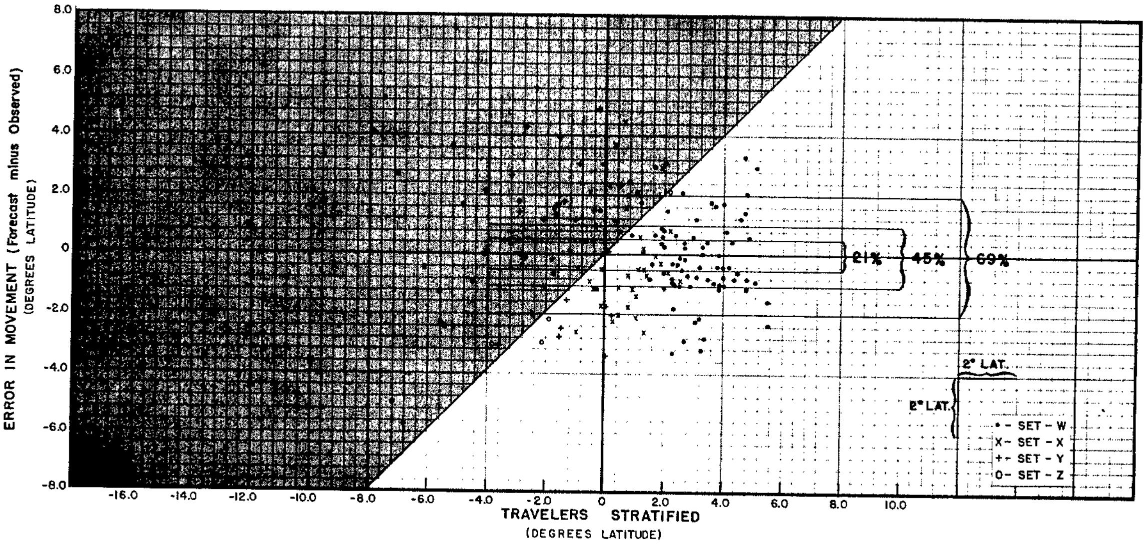

Figure 3.2e. 24-Hour Forecast (Zonal Component) Error Distribution; Modified Travelers (Stratified) Forecast Versus Forecast Error.

4. SUMMARY AND CONCLUSIONS

In summary, an attempt has been made to take existing objective and semiobjective hurricane forecast techniques and combine two or more of them into a single objective forecast technique which, hopefully, will produce a more accurate and more objective forecast than is presently possible by experienced forecasters. A forecast only as accurate as the official forecast would still be desirable, providing it were objectively obtained.

The results, although not outstanding, are encouraging. Two methods were found to be statistically better than the official forecasts. Because of the absence of independent data, however, no firm statement as to their accuracy can be made at this time. It must be pointed out, however, that even if these equations had proven to be far superior, they (except for the modified Travelers technique) would have little operational value because the predictors are not all available when needed (at warning time). The equations do, however, indicate that it is feasible to combine the objective methods with some success. The next step would be to attempt a similar study on longer term forecast periods, 36 to 48 hours for example, as soon as sufficient data of this type is available. Forecasts of this duration would be of great value to those responsible for the accurate predictions of hurricane movements.

The modified Travelers technique, after stratification by past movement, was the one set of equations of operational value which did result from this study. Although its improvement over the official forecast is small, it is objective and available at warning time.

One fact that became very obvious during this study was the need for some form of stratification. Two methods were used in this study, one by region of occurrence (geographic location) and the other by past 12-hour movement. Stratification of the data by other schemes could possibly produce better results than obtained in this study.

However, until more hurricane forecasts become available, a true evaluation of the equations can not be made. For this reason, the equations were sent to the Fleet Weather Facility (FWF) at Miami for operational evaluation, early in the 1963 hurricane season. Predictions using these equations will be made whenever possible and the results will be sent to the Navy Weather Research Facility for evaluation. With an accumulation (several seasons) of these results it is hoped to learn more definitely the true merit of the work reported here.

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1. AROWA, *"Prediction of Tropical Cyclone Tracks,"* *Second Research Report Task 12, AROWA 12-0755-141.* pp. 40, July 1955.

2. MILLER, B. I. and P. L. MOORE, *"A Comparison of Hurricane Steering Levels,"* *Bulletin of the American Meteorological Society.* 41, pp. 59-67, 1960.

3. TRACY, J. D., *"Verification of Forecasts of Hurricane Motion Using Various Techniques,"* *National Hurricane Research Project Report No. 50, Proceedings of the Second Technical Conference on Hurricanes.* pp. 373-382, 1961.

4. VEIGAS, KEITH W., *"Prediction of Twelve, Twenty-four and Thirty-six Hour Displacement of Hurricanes by Statistical Methods, Final Report."* *Contract No. Cwb-9807,* The Travelers Research Center, Inc., Hartford, Conn., pp. 36, 1961.

APPENDIX A

The AROWA (Riehl-Haggard) Objective Method of Predicting 24-Hour Tropical Cyclone Movement [1].

Two tools are necessary to make the AROWA forecast; a current 500-mb. chart and the grid shown in figure A-1. With these, predictions of meridional and zonal components of storm movement can be made by following the procedure listed below.

A.1 Meridional Displacement

1. Mark, on the 500-mb. chart, the present *surface* position of the storm center.

2. Place the grid (oriented north-south) on the 500-mb. chart and over the present surface position, using, as the grid center, the central longitude (heavy line) and the 5° latitude line which is nearest to the storm's present position on the chart.

3. Determine the height of the 500-mb. surface at 7.5° of *longitude* east and at 7.5° west of the center, at the points of intersection with the latitude lines at 5° and 2.5° of *latitude* south of the center, at the latitude of the storm, and at 5° and 2.5° of *latitude* north of the center for the first approximation. Record the heights to the nearest ten feet[1] on the computation sheet (fig. A-2).

4. Subtract the west heights from the east heights and total (add up) these height differences. To convert this figure to a height difference per 5° of *longitude*, first divide by the number of height differences (in this case five), which gives the average height difference of the sector per *15°* of *longitude* and second divide this figure by three to get the average height difference per 5° of longitude. (See step I-1 on the computation sheet.)

5. Using the above average meridional height difference per 5° of longitude and the midlatitude of the sector of the grid being used (in this approximation, the present position of the storm) enter the diagram (figure A-3) and read the 24-hour meridional displacement in degrees of latitude, along the meridional displacement line at the *top* of the diagram. This

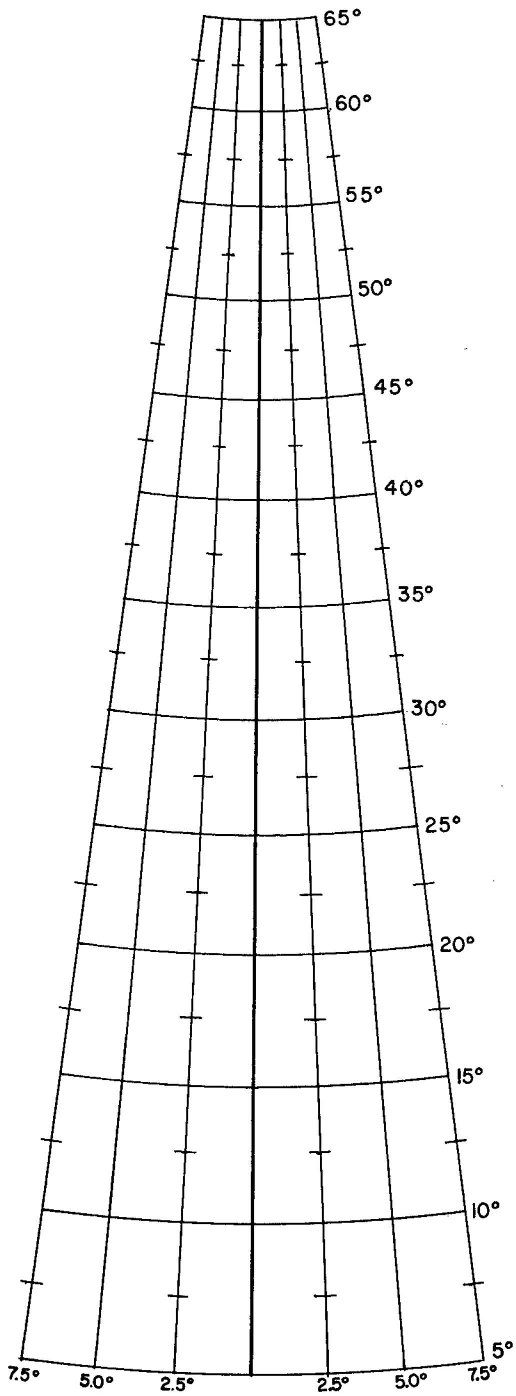

Figure A-1. Grid Used for Making the AROWA and Miller-Moore 24-Hour Hurricane Forecast.

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[1] *The AROWA method was derived when the standard unit of height on the upper-level charts was in feet, thus when applying the method to current charts (which are in meters), the heights must first be converted from meters to feet before entering the computation sheet. (Divide the height in meters by 0.3048 m./ft. to give feet.)*

STORM ________	WARNING NO. ________ MAP DATE/TIME ________

MERIDIONAL COMPONENT

	Height		
	7.5° E.	7.5° W.	ΔH, (E.–W.)
12.5° N.	____ -	____ =	____
10.0° N.	____ -	____ =	____
7.5° N.	____ -	____ =	____
5.0° N.	____ -	____ =	____
2.5° N.	____ -	____ =	____
0	____ -	____ =	____
2.5° S.	____ -	____ =	____
5.0° S.	____ -	____ =	____
(1st Approx $\Sigma\Delta H$(to 5.0° N.) =			____
Total of Differences			____

1st Approximation

ZONAL COMPONENT

	Height		
	N.	5.0°S.	ΔH, (N.–S.)
7.5° W.	____ -	____ =	____
2.5° W.	____ -	____ =	____
2.5° E.	____ -	____ =	____
7.5° E.	____ -	____ =	____
Total of Differences			____

I. MERIDIONAL CALCULATIONS

1. $\frac{\text{Total Meridional Height Differences}}{\text{No. of Height Differences} \times 3} = \frac{\_\_\_\_}{\times 3} = \_\_\_\_.$

2. Use Latitude of Midpoint and Step 1 to Enter Figure A-3 to Give________°
Toward______________.

3. For Second Approximation Include 7.5° North of Storm Latitude and Repeat Steps 1 and 2
$\frac{\_\_\_\_}{\times 3} = \_\_\_\_ = \_\_\_\_$°Toward______.

4. For Third Approximation Include 10.0° North of Storm Latitude and Repeat Steps 1 and 2
$\frac{\_\_\_\_}{\times 3} = \_\_\_\_ = \_\_\_\_$°Toward______.

5. For Fourth Approximation Include 12.5° North of Storm Latitude and Repeat Steps 1 and 2
$\frac{\_\_\_\_}{\times 3} = \_\_\_\_ = \_\_\_\_$°Toward______.

II. ZONAL CALCULATIONS

1. $\frac{\text{Total Zonal Height Differences} \times 5}{4 \times \text{Latitude Width of Grid}} = \frac{\_\_\_\_ \times 5}{4\times} = \_\_\_\_.$

2. Use Latitude of Midpoint and 1 to Enter Figure A-3 to Give______°Toward______.

DATE/TIME__________Z PRESENT POSITION______N.______W.
MERIDIONAL AND ZONAL CALCULATIONS______________________
DATE/TIME__________Z 24-HOUR FCST. POST.______N.______W.

Figure A-2. AROWA 24-Hour Forecast Computation Sheet.

figure is the first approximation. Record this value in step I-2 of the computation sheet.

6. If this displacement figure is less than 1.3° of latitude northward or if it is southward, *no* further approximations are necessary and the displacement in step I-2 of the computation sheet is the 24-hour forecast of meridional (north-south) movement. If the displacement is between 1.3° and 3.7° of latitude (northward) inclusive, an additional east-west height difference, 7.5° north of the center, is incorporated into the calculations (step I-3). If the first approximation is greater than 3.7° and equal to or less than 6.2° of latitude, two additional east-west differences, 7.5° and 10.0° north of the center, are used (step I-4). Table A-1 illustrates how the first approximation meridional components are grouped and the additional number of grid points, north of the center, which should be used when the first approximation exceeds 1.2° latitude. The table also includes the number of degrees of latitude which must be added to the latitude of the storm when calculations are carried beyond the first approximation. This figure represents the midlatitude of the grid sector being used and is needed to enter the diagram (fig. A-3) in the proper latitude.

7. The computations are terminated when a computed meridional displacement falls in the same (or lesser) meridional displacement group (see table A-1) as the previous computation. The larger value of these two approximations is used as the forecast meridional movement.

8. The following rules should be noted:

(a) Only one approximation is made if the displacement is *southward* .

(b) If the sense of the east-west gradient reverses between the latitude of the storm and 5° to the south, then the points at the lowest latitude (at 5°) are omitted from the calculation.

(c) If the second or third approximations reach into a belt where the sense of the east-west gradient reverses from that in the belt 5° north to 5° south of the center, then the caclulation is terminated.

(d) If the east-west extent of the grid reaches beyond a trough or ridge line (in the wave pattern of the basic current), then the read-out

TABLE A-1. Determination of the Latitudinal Extent of the Grid to Be Used in Making the AROWA Forecast.

First Approximation Meridional Movement (°Latitude)	*Grid Points to be Added North of Center*	*°Latitude to be Added to Storm Center Position*
0 to 1.2	*none*	*0*
1.3 to 3.7	*7.5°*	*1.25°*
3.7 to 6.2	*7.5°, and 10°*	*2.50°*
6.3 to 8.7	*7.5°, 10.0°, and 12.5°*	*3.13°*
8.8 to 11.2	*7.5°, 10.0°, 12.5°, and 15.0°*	*5.00°*

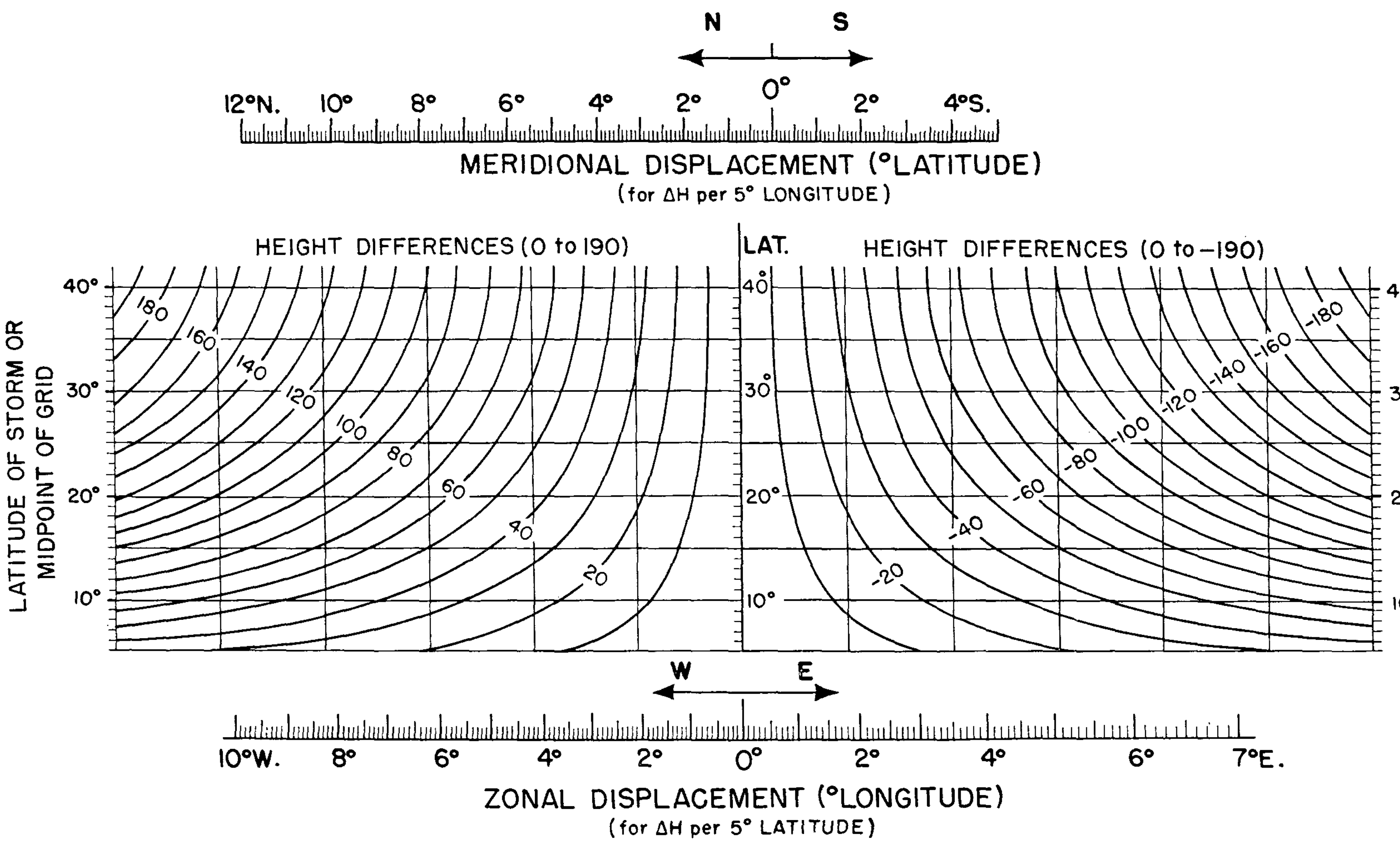

Figure A-3. *A Diagram for Use in Determining Meridional and Zonal Displacement. This Diagram is Entered with the Height Difference and the Midlatitude of the Grid, the Adjusted Meridional or Zonal Component is Then Read Directly at the Top or Bottom of the Diagram.*

of 500-mb. heights should be terminated at the trough or ridge line and thus should not be extended to 7.5° east and west (the calculation should be kept symmetrical). The computation sheet has not been designed to take care of the situation; as it is set up to give the height difference *(ΔH)* per 5° of longitude, as needed in the diagram (fig. A-3). If this situation occurs, the user simply has to divide the average meridional height difference by the actual number of degrees (longitude) of the grid used. This will yield the average difference per degree; multiplying them by five gives the difference in suitable form for the diagrams (fig. A-3).

A.2 Zonal Displacement

1. Determine the 500-mb. height at points 2.5° and 7.5° of longitude east *and* west of the center, at 5° latitude *south* of the *present* position, and 5° *north* of the *final* storm position as determined by the northward (or southward) meridional computation. The northward points, however, should in no case be placed beyond 10° of latitude north of the initial storm position. (Note: some of the points used in this step, have previously been used for the meridional computation.)

2. Subtract the south heights from the north heights and total these differences (see fig. A-2). Convert this height difference to a height difference per 5° of *latitude* by using step II-1 on the computation sheet. (The total of the zonal height differences divided by four equals the average height difference for the grid sector, dividing this by the latitude width of the grid equals the average height difference per degree; multiplying by 5° gives the average height difference per 5° of latitude.)

3. Using this height difference and the mid-latitude of the grid (initial latitude plus one half of meridional displacement) enter the diagram (fig. A-3) and at the *bottom* read the 24-hour zonal displacement in degrees longitude along the zonal displacement line. The 24-hour forecast position is obtained by adding the calculated meridional and zonal movements to the present position.

APPENDIX B

Instructions for Predicting 24-Hour Hurricane Movements by the Miller-Moore Forecast Method [2]

This method is similar to the AROWA method (see appendix A); it differs mainly from the AROWA method in that it uses the 700-mb. chart rather than the 500-mb. chart. A grid similar to the AROWA grid (fig. A-1) is used, except that for *zonal* computations, heights are read at intervals of 2.5° of longitude instead of 5.0° intervals.

The following instructions, along with the included graphs and computation sheets, provide the information necessary for making the Miller-Moore forecast.

B.1 Meridional Component

1. Mark the present *surface* position of the storm center on the 700-mb. chart.

2. Place the grid (fig. A-1), oriented north-south, over the storm's present *surface position*, using the 5° latitude line which is nearest to the storm's present position and the center meridian on the grid as the grid center.

3. Record the height of the 700-mb. surface on the computation sheet (fig. B-1a), at 7.5° of longitude east *and* 7.5° west of the surface center, at the points of intersection with latitudes of 2.5° and 5.0° of latitude south of the center and at 2.5°, 5.0°, 7.5°, and 10° of latitude north of the center.

4. Subtract the west heights from the east heights and record.

5. First approximation (fig. B-1a. step II):

(a) Find the sum of the height difference $(\Sigma \Delta H)$ from 5° south to 5° north of the current surface center. If the sum of the height differences comes out negative a southward component is indicated and only one approximation is used.

(b) Divide this sum by 30 to obtain the height gradient per 2.5° of longitude. (The total height difference divided by the number of height differences (5) equals the average height difference for this particular grid sector, dividing by 15 (i.e., 7.5 + 7.5) equals the average height difference per degree of longitude, multiplying by 2.5 equals the average height difference per 2.5° of longitude.

(c) Enter figure B-2 with the average height difference per 2.5° of longitude (either positive or negative) and the latitude of the midpoint of the grid sector being used to obtain the meridional geostrophic component (v_7) in knots. The latitude of the midpoint of the grid sector, in this case, is the latitude of the current surface center and is called the "initial" latitude.

(d) If $\Sigma \Delta H$ in step (a) is negative, then take the figure obtained in step (c), (v_7), and proceed to step V. If $\Sigma \Delta H$ is positive and v_7 (from step c) is 6.5 knots or less, perform the second approximation; if $\Sigma \Delta H$ is greater than 6.5 knots, skip the second approximation and go directly to the third approximation.

6. Second approximation (fig. B-1a, step III):

(a) Find the sum of the height differences $(\Sigma \Delta H)$ from 5° south to 7.5° north of the current surface center.

(b) Divide this sum by 36 to obtain the height gradient per 2.5° of longitude.

(c) Enter figure B-2 with the height gradient obtained in step (b) and the latitude of the midpoint of the grid to obtain the meridional geostrophic component in knots. The latitude of the midpoint of the grid, in this case, is the initial latitude plus 1.25° of latitude, half the distance the grid is ex-

MERIDIONAL COMPONENT (sheet 1)

I. Record 700-mb. heights and E.-W. differences.

	7.5° E.		7.5° W.		ΔH, (E.–W.)
10.0° N.	______	-	______	=	______
7.5° N.	______	-	______	=	______
5.0° N.	______	-	______	=	______
2.5° N.	______	-	______	=	______
0	______	-	______	=	______
2.5° S.	______	-	______	=	______
5.0° S.	______	-	______	=	______

II. First Approximation
- A. $\Sigma\Delta H$ (to 5.0° N.) = ______
- B. $\Sigma\Delta H \div 30$ = ______
- C. Lat. Mid. Pt. (initial lat. +0°) = ______ ° N.
- D. Using B and C get v_7 from fig. B-2 = ______ Knots

If $\Sigma\Delta H$ is negative go to step V.
If $\Sigma\Delta H$ is positive go to step III.

III. Second Approximation
- A. $\Sigma\Delta H$ (to 7.5° N.) = ______
- B. $\Sigma\Delta H \div 36$ = ______
- C. Lat. Mid. Pt. (initial lat. +1.25°) = ______ ° N.
- D. Using B and C get v_7 from fig. B-2 = ______ Knots

Use larger of first and second approximation in step V if v_7 is equal to or less than 6.5 knots, if greater than 6.5 knots proceed to step IV.

IV. Third Approximation
- A. $\Sigma\Delta H$ (to 10.0° N.) = ______
- B. $\Sigma\Delta H \div 42$ = ______
- C. Lat. Mid. Pt. (initial lat. +2.5°) = ______ ° N.
- D. Using B and C get v_7 from fig. B-2 = ______ Knots

Use larger of second or third approximation for step V.

V. Movement Component
- A. Appropriate v_7 = ______ Knots
- B. P_y (past 12-hour lat. movement in ° lat.) × 5
  ______ ° lat. × 5 = ______ Knots
- C. Enter fig. B-3 with A and B to give forecast speed, $\overline{V}$ = ______ Knots
- D. 6-hr. movement component ($.1\overline{V}$) = ______ (°lat.)
- E. 12-hr. movement component ($.2\overline{V}$) = ______ (°lat.)
- F. 24-hr. movement component ($.4\overline{V}$) = ______ (°lat.)

Figure B-1a Miller-Moore Hurricane Forecast Computation Sheet 1 (of Two).

ZONAL COMPONENT (sheet 2)

I. Record 700-mb. heights and N.-S. differences.

____ ° N. latitude =[initial lat. + $(.2\overline{V})^\circ$ + 5.0°]		____ ° S. latitude = [initial lat. -5.0°]		ΔH, (N.–S.)
7.5° W. ____	—	____	=	____
5.0° W. ____	—	____	=	____
2.5° W. ____	—	____	=	____
0 ____	—	____	=	____
2.5° E. ____	—	____	=	____
5.0° E. ____	—	____	=	____
7.5° E. ____	—	____	=	____
		ΣΔH	=	____

II. ΣΔH/2.5° Calculation

A. ΣΔH = ____

B. °Lat. N. [initial lat. +$(.2\overline{V})^\circ$ +5.0°] = ____ °lat.

C. °Lat. S. [initial lat. -5.0°] = ____ °lat.

D. Grid Width °lat. (B-C) = ____ °lat.

E. $\Sigma\Delta H/2.5^\circ = \dfrac{\Sigma\Delta H \times 2.5}{7\times(\text{Grid Width})}$

$= \dfrac{\_\_\_\_}{7\times(\_\_\_\_)} \times 2.5 =$ ____ °lat.

III. u_7 Calculation

A. Lat. Mid. Pt. [initial lat. +$(.1\overline{V})^\circ$] = ____ ° N.

B. Using ΣΔH/2.5° (II-E) and Lat. Mid. Pt. (A) get u_7 from fig. B-4 = ____ Knots

IV. Zonal Component

A. u_7 (from III-B) = ____ Knots

B. P_x, (past 12-hour long. movement in °lat.) × 5
____ °lat. × 5 = ____ Knots

C. Enter fig. B-3 with A and B to get forecast speed, $\overline{U}$ = ____ Knots

D. 12-hr. movement component $(.2\overline{U})$ = ____ °lat.

E. 24-hr. movement component $(.4\overline{U})$ = ____ °lat.

V. Convert Component to Degrees Longitude
24-hr. component in °lat. × $\dfrac{1}{\cos\phi}$ of the lat. = ____ °long.

Initial Position ____ ° N. ____ ° W. plus the meridional and zonal movement components ____ ° N. ____ ° W. equals the 24-hour forecast position ____ ° N. ____ ° W.

Figure B-1b Miller-Moore Hurricane Forecast Computation Sheet 2 (of Two).

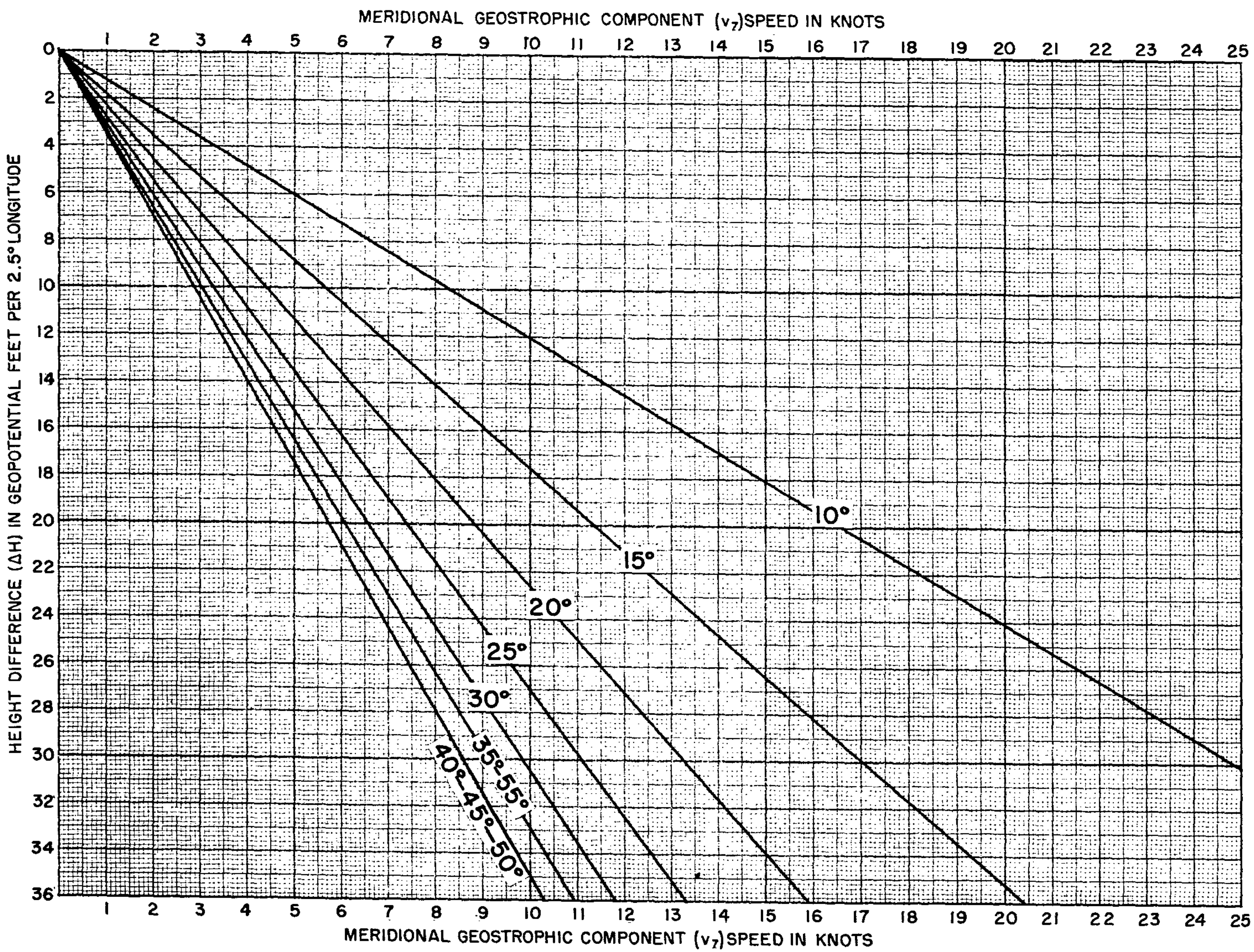

Figure B-2. *Curves for Deriving the 700-Mb. Geostrophic Meridional Component Surrounding a Storm.*

tended.

(d) Make a third approximation if the larger of the first and second approximations is more than 6.5 knots.

7. Third approximation (fig. B-1a, step IV):

(a) Find the sum of the height differences $(\Sigma\Delta H)$ from 5° south to 10° north of the current surface center.

(b) Divide this sum by 42 to obtain the height gradient per 2.5° of longitude.

(c) Enter figure B-2 with the height gradient obtained in step (b) and the latitude of the midpoint of the grid to obtain the meridional geostrophic component in knots. The latitude of the midpoint of the grid in this case is the initial latitude plus 2.5° of latitude.

8. Forecast meridional speed component (fig. B-1a, step V):

Select the meridional geostrophic component from the first, or second, or third approximations, whichever the case may be. (The first approximation is used if a south component is indicated. If, however, the first approximation results in a northerly component of movement, the second approximation is worked, and the larger of the first and second approximations is used, if the value is 6.5 knots or less. If either value exceeds 6.5 knots a third approximation is made and the larger of these approximations is selected.)

(a) Enter figure B-3 with the selected meridional geostrophic component (v_T) and the meridional persistence speed component, P_y, to obtain the forecast meridional speed component $(\overline{V})$ in knots; P_y is the speed at which the storm has been traveling in a north-south direction for the past 12 hours as determined from the best available track. This factor is negative if the direction is south. It can be found by taking the difference between the present latitude position and the past 12-hour position, multiplying by 60 nautical miles per degree of latitude and dividing by 12 hours, which gives P_y in knots (see step V-B of computation sheet). Note that figure B-3 consists of two graphs, one for use when the initial latitude of the storm is at or south of 27.5° N. (fig. B-3a) and one for use when the initial position of the storm is north of 27.5° N. (fig. B-3b).

(b) Convert the forecast speed from knots to 24-hour forecast movement in degrees of latitude by multiplying by .4, (i. e., speed in degrees of latitude equals speed in nautical miles per hour $(\overline{V})$, times one degree latitude per 60 nautical miles, times 24 hours).

9. Retraction of the grid in an east-west direction:

In making the meridional computations, the grid should not be extended through a polar trough to the west or to the east, if in doing so the sense of the height gradient becomes reversed. In these cases retract the grid in equal 2.5° of longitude increments from the east and west. When this is done, the factors (30, 36, and 42) shown for computing the height gradient per 2.5° increment of longitude are not applicable. When the grid is retracted, compute the gradient by dividing the total height difference by the product of the number of height differences north to south and the number of 2.5° increments east to west.

B.2 Zonal Component

1. Determine the north and south boundaries of the grid. The north boundary is the initial latitude of the storm center plus the 12-hour meridional component $(.2V)$ plus 5° of latitude. The south boundary is the initial latitude minus 5° of latitude.

2. Using the computation sheet (fig. B-1b), record the 700-mb. heights from 7.5° of longi-

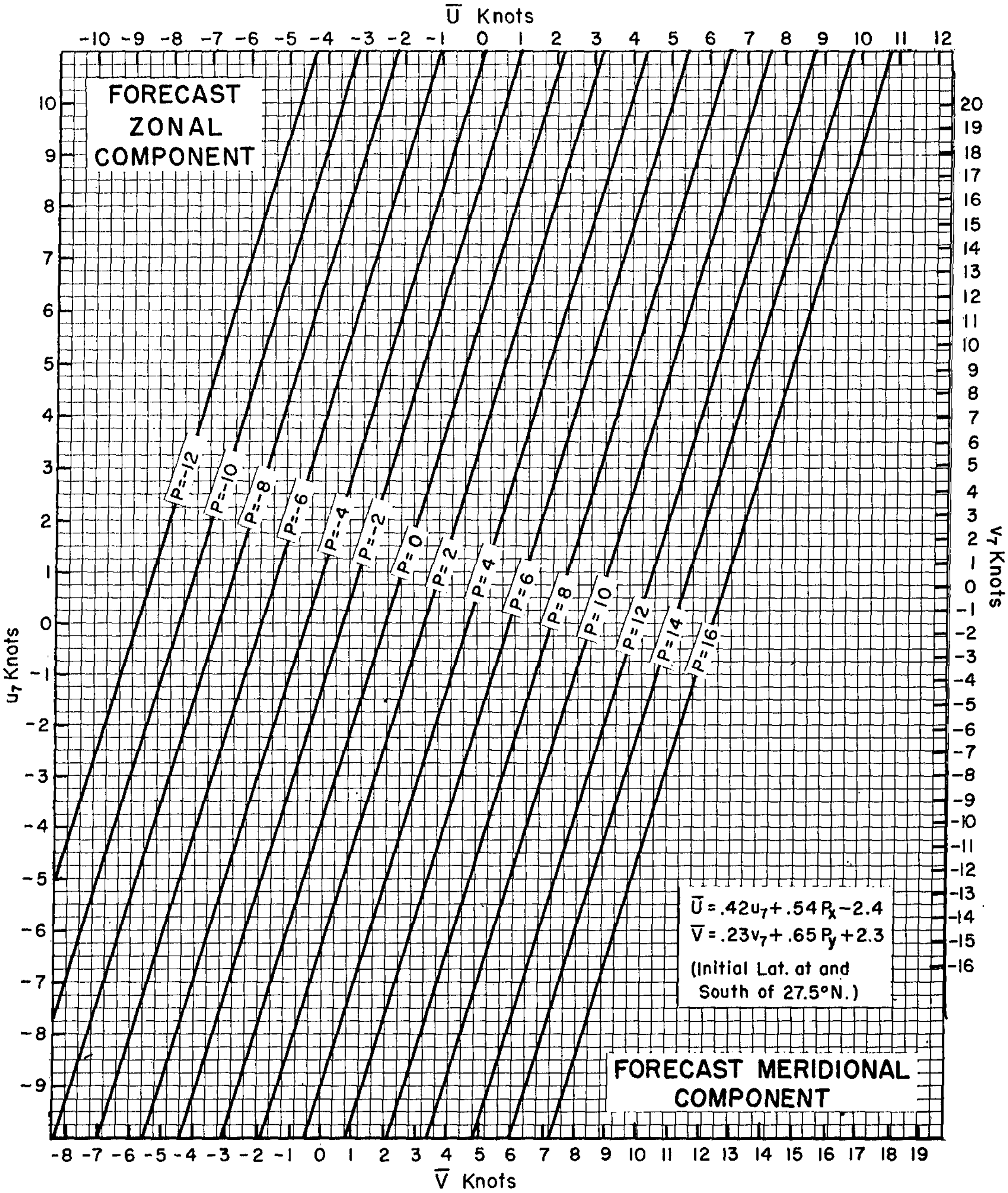

Figure B-3a. Curves for Obtaining the Forecast Meridional Speed Component and the Forecast Zonal Speed Component Using the Appropriate Geostrophic Component and Persistence Speed Component (at or South of 27.5 °N.).

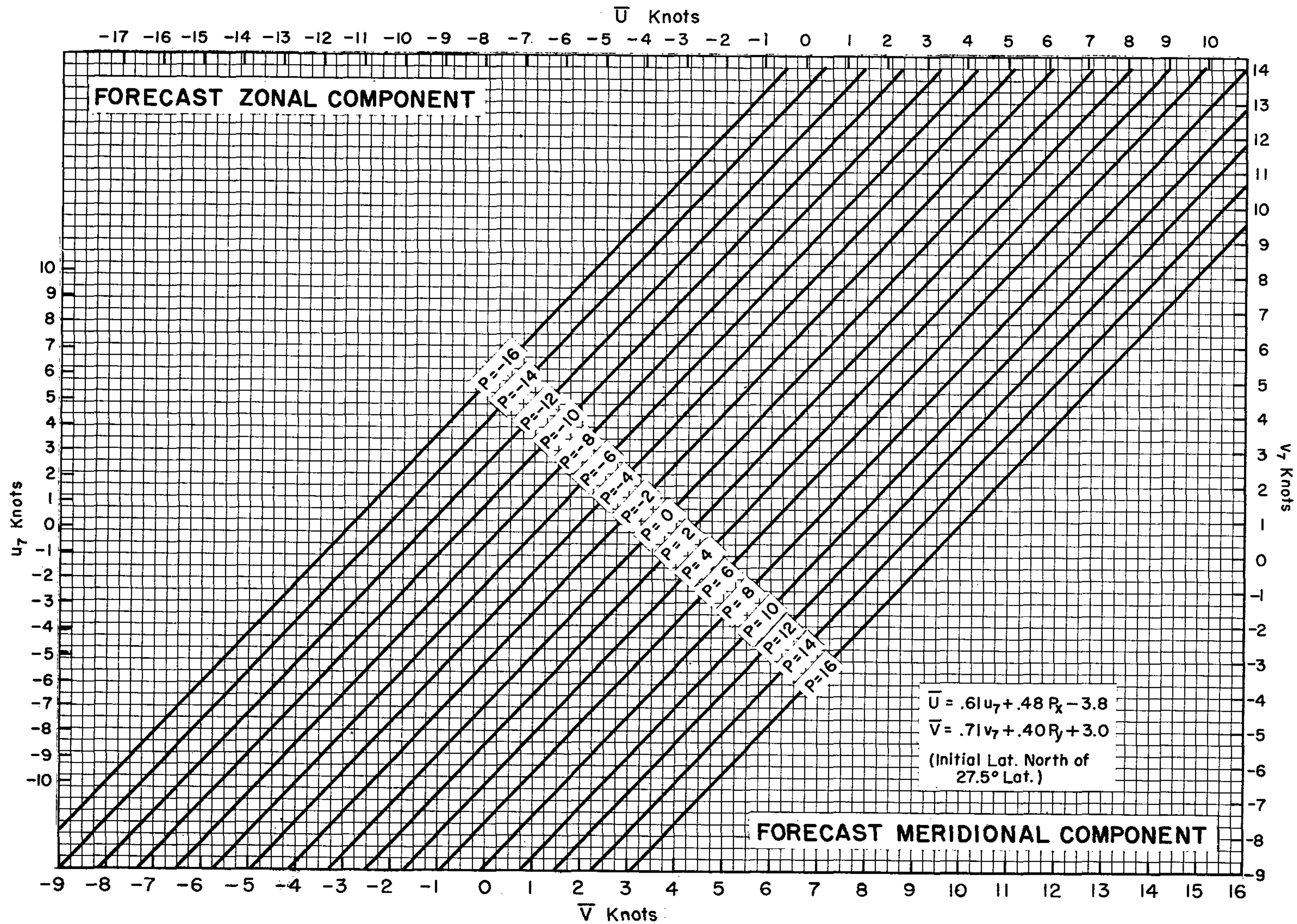

Figure B-3b. ***Curves for Obtaining the Forecast Meridional Speed Component and the Forecast Zonal Speed Component Using the Appropriate Geostrophic Component and Persistence Speed Component (North of 27.5 °N.).***

tude west of the storm center to 7.5° east, at 2.5° intervals along the north and south boundaries, and compute and record the height differences, north minus south. Find the total of the height differences, $\Sigma\Delta H$.

3. Find the height gradient per 2.5° of latitude by dividing the total height difference by 7 times the latitude width of the grid sector being used, to give the height gradient per degree, then multiply by 2.5 to give the gradient per 2.5° of latitude (fig. B-1b step II).

4. Enter figure B-4 with the height gradient ($\Sigma\Delta H/2.5°$ lat.) and the latitude of the midpoint of the grid to find the zonal geostrophic speed component (u_7). The latitude of the midpoint of the grid, in this case, is the initial latitude plus the 6-hour meridional component, $.1\bar{V}$ (fig. B-1b step III).

5. Forecast zonal speed component (fig. B-1b step IV):

(a) Enter figure B-3 with the zonal geostrophic speed component (u_7) and the zonal persistence speed component (P_x) to obtain the forecast zonal speed component $(\bar{U})$; P_x is the speed at which the storm has been traveling in an east or west direction during the past 12 hours. This factor is negative if the direction is toward the east. It is computed in a similar fashion as P_y.

(b) Compute and record the 12- and 24-hour forecast zonal speed components in degrees of latitude, as shown in step IV of the computation sheet.

(c) Convert the 24-hour forecast zonal component from degrees latitude to degrees longitude (fig. B-1b step V). The 24-hour forecast position is found by simply adding the 24-hour meridional (north-south) forecast component to the present position latitude and the 24-hour forecast zonal (east-west) component to the present position longitude.

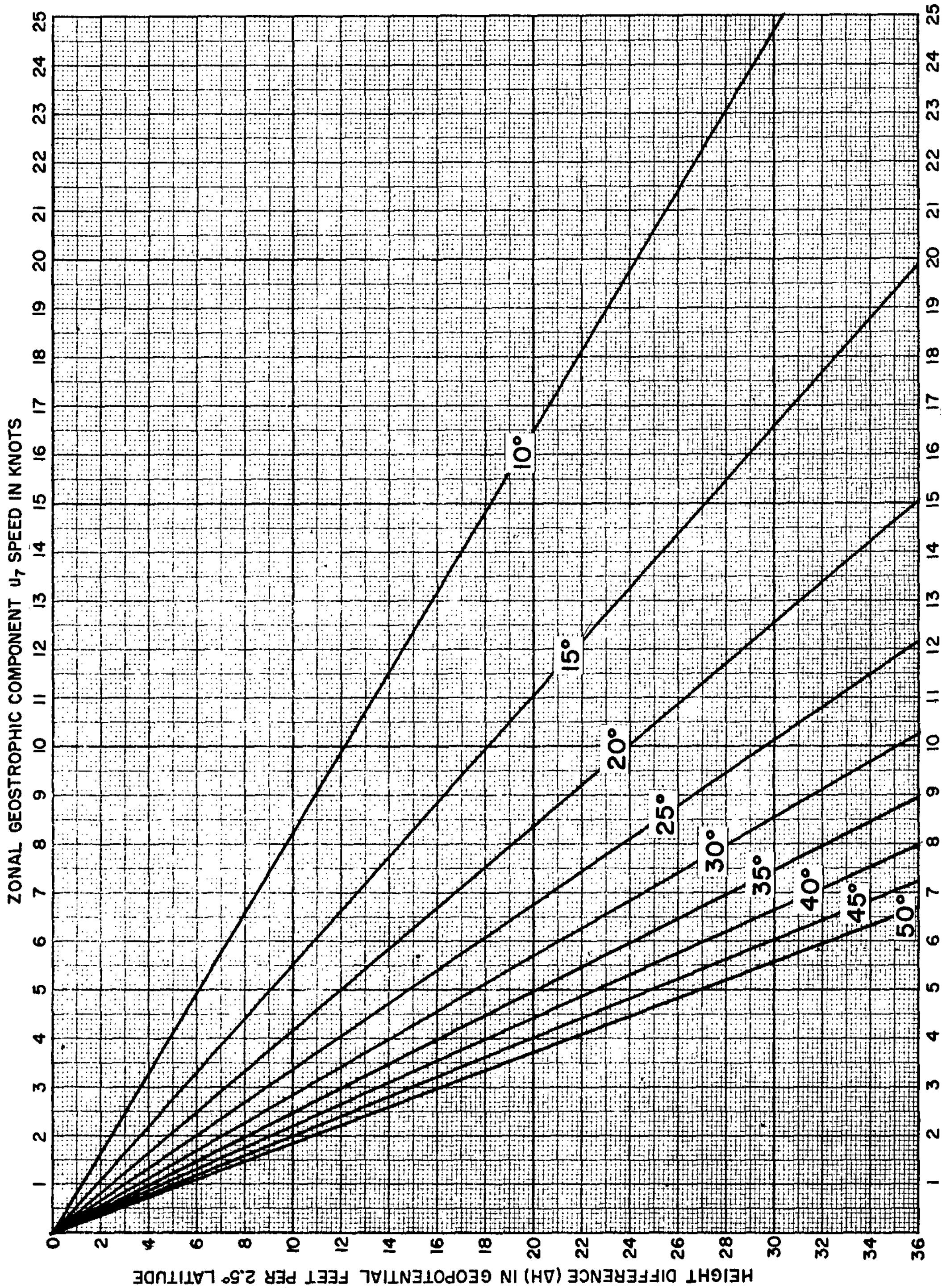

Figure B-4. Curves for Deriving the 700-Mb. Geostrophic Zonal Component Surrounding a Storm.

APPENDIX C

Instructions for Predicting 24-Hour Hurricane Movements

by the 1960 Travelers Method [4].

The Travelers computation is divided into two zones, depending on the initial latitude of the storm center. The southern zone includes storms whose initial latitude is at or south of 27.5° N. The northern zone includes storms whose initial latitude is at or north of 26.0° N. Thus, there is a zone where either computation may be used. The choice of computation for the overlapping zone is subjective. In this work the southern zone computation was used to 27.5° N. because of the greater and faster availability of surface data, which is the only data required in this zone. The northern zone required 500-mb. data in addition to surface information.

To facilitate computations, a grid is used. Figures C-1, C-2, and C-3 are for the southern zone and are to be used from 12.5° N. to 17.4° N., 17.5° N. to 22.4° N., and 22.5° N. to 27.4° N., respectively. Tables C-1 and C-2 contain the reference points which will enable the reader to more easily construct the grids for his particular scale map.

C.1 Southern Zone Computations

The southern zone computations require only sea level pressures and the past 12-year movement of the storms.

C.1.1 Latitude Movement

The equation for the 24-hour forecast of latitude displacement *($\Delta\phi$)* is:

$$\Delta\phi = 7.90 + 0.0841 \times (3) + 0.1418 \times (10) - 0.0976 \times (11) - 0.1357 \times (7) \pm 1.0327 \times P_y$$

A positive value for $\Delta\phi$ indicates a forecast of north movement, whereas a negative value indicates a south movement; the whole numbers (3), (10), (11), and (7) represent points at which the sea level pressures in millibars and tenths (i. e., 1013.2) are picked off the grid, after the grid has been placed over the present position of the storm. The other numbers in the equation are simply multipliers. The factor P_y in the last term of the equation *($\pm 1.0327 \times P_y$)* represents the past 12-hour *meridional* motion of the storm, measured in degrees latitude; if P_y is north, then the plus sign is used in the equation, if south, the minus sign is used.

Detailed procedure for the computation of the latitude displacement (use computation sheet, figure C-7):

(a) Depending on the past 12-hour movement of the storm, enter P_y in either the total of minus terms or the total of plus terms, in degrees of latitude (to the nearest tenth; i. e., 5.1°) on the computation sheet.

(b) Select the southerly grid (one of three), corresponding to the initial latitude of the storm.

(c) Place the center of the grid (circle with dot) on present position of the storm, and, using the two dashed lines on the grid, align the grid parallel to the longitude lines of the surface map.

(d) Read the sea level pressures from the surface map at the appropriate grid points (the whole numbers in parentheses on the computation sheet) and enter on the computation sheet to the nearest tenth of a millibar (i. e., 1012.1) and multiply by the appropriate constant.

(e) Add the minus terms.

(f) Add the plus terms.

(g) Subtract the minus terms from the plus terms. The answer is the 24-hour latitudinal forecast movement. A positive value indicates a north movement in latitude and a negative value a south movement.

C.1.2 Longitudinal Movement

The equation for the 24-hour forecast of longitude displacement *($\Delta\lambda$)* is:

$$\Delta\lambda = 50.60 + 0.0571 \times (2) + 0.2378 \times (8) + 0.0228 \times (9) - 0.1958 \times (11) - 0.1730 \times (12) \pm 1.2873\ P_x$$

A positive value for $\Delta\lambda$ indicates a west

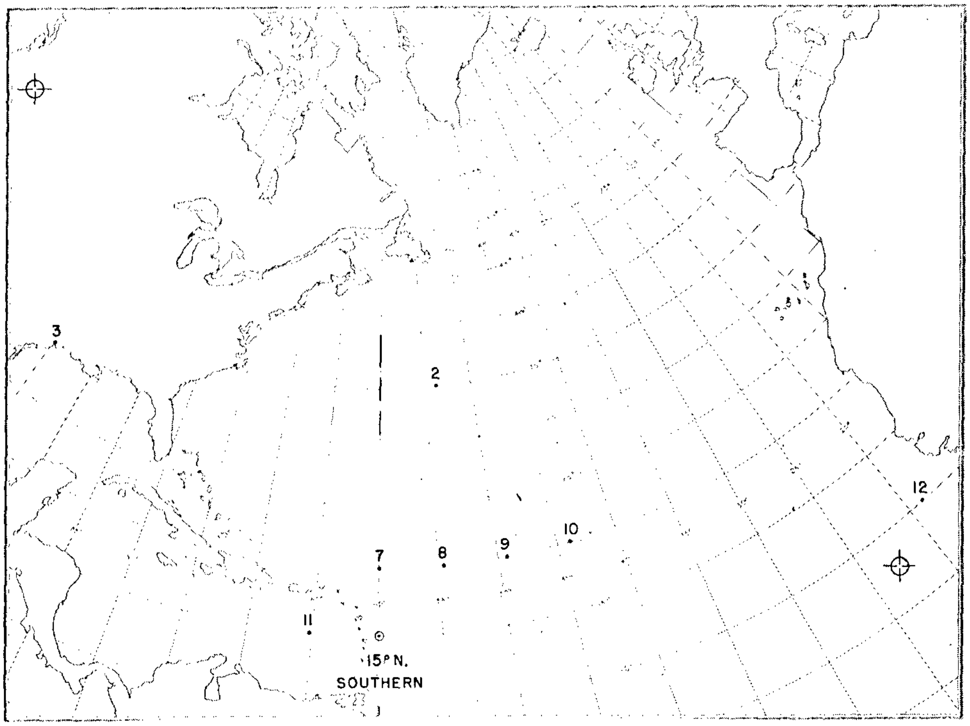

Figure C-1. Southern Zone Grid Used to Obtain Travelers 24-Hour Hurricane Movement Forecast for Storms Located Between 12.5 ° N. to 17.4 ° N.

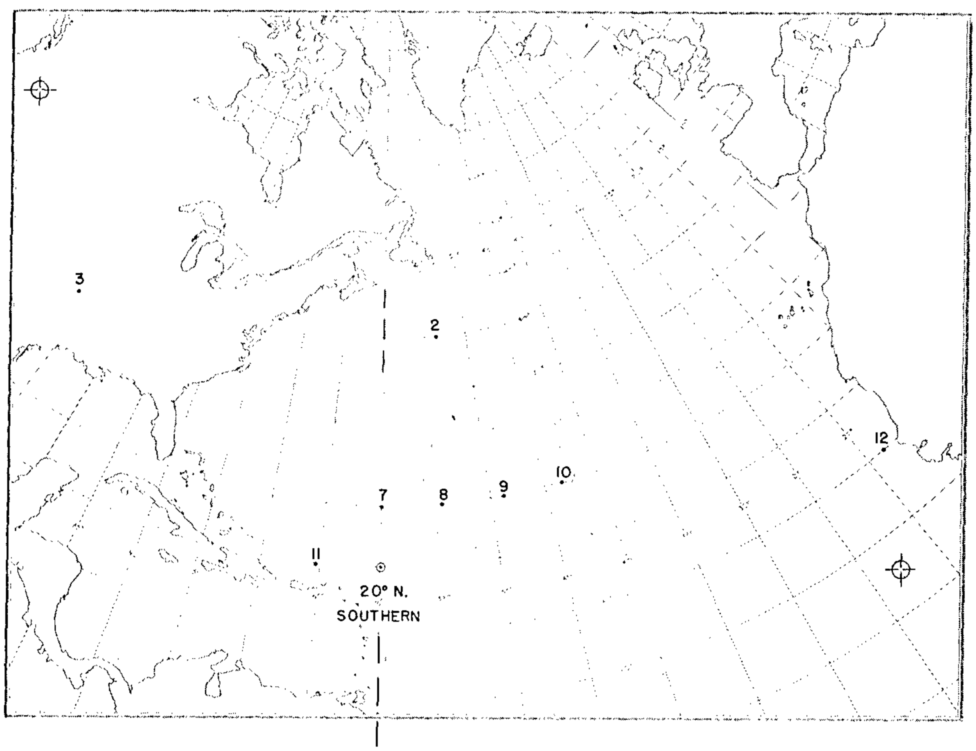

Figure C-2. Southern Zone Grid Used to Obtain Travelers 24-Hour Hurricane Movement Forecast for Storms Located Between 17.5 ° N. to 22.4 ° N.

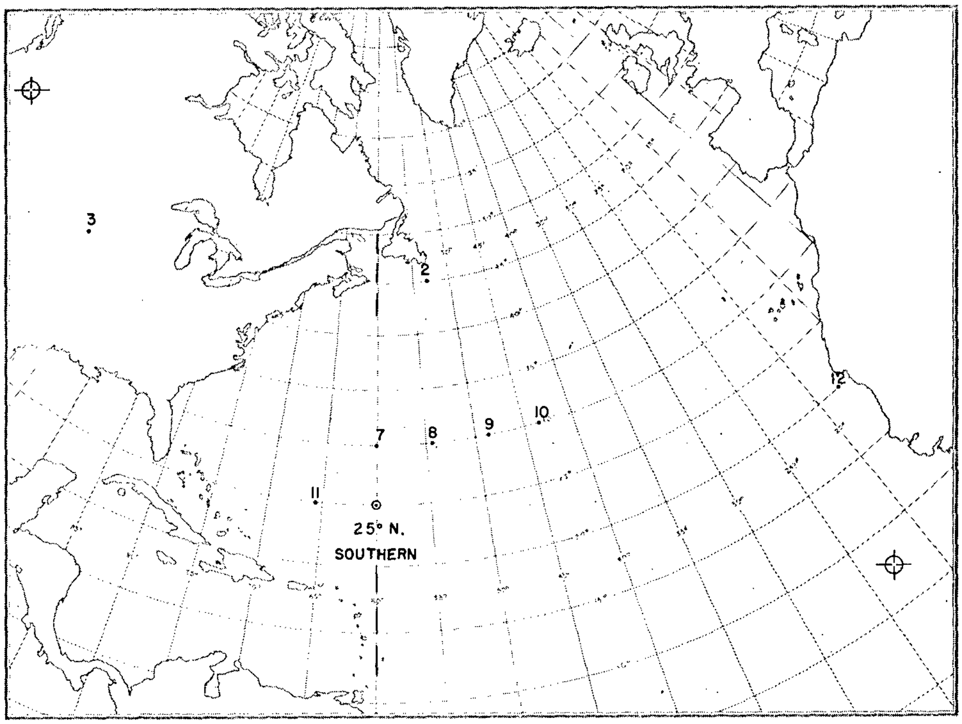

Figure C-3. Southern Zone Grid Used to Obtain Travelers 24-Hour Hurricane Movement Forecast for Storms Located Between 22.5 °N. to 27.4 °N.

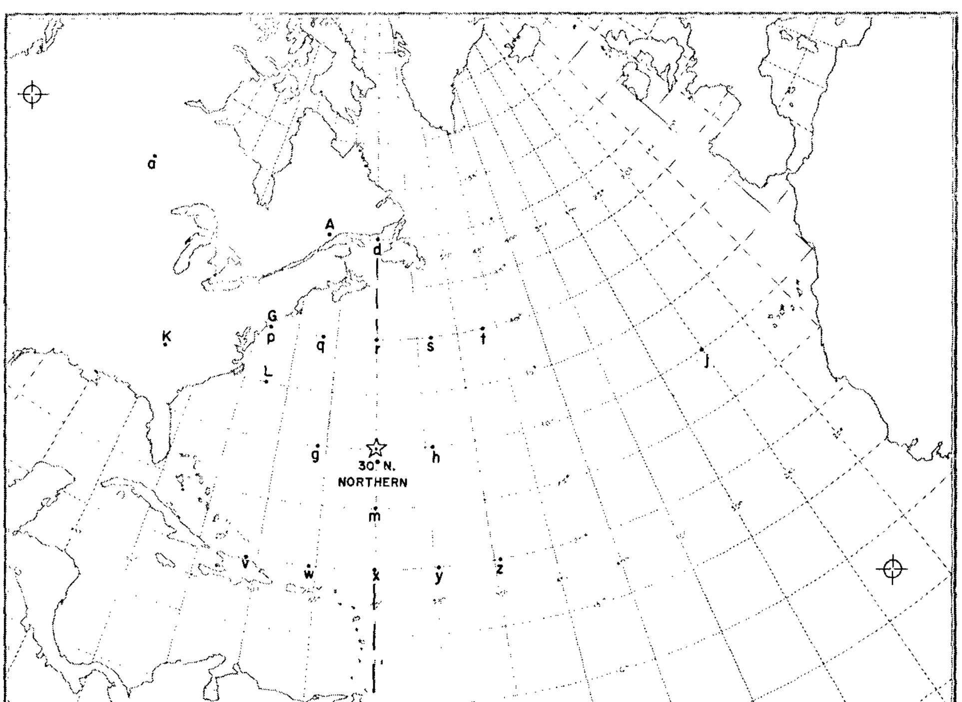

Figure C-4. Northern Zone Grid Used to Obtain Travelers 24-Hour Hurricane Movement Forecast for Storms Located Between 27.5 °N. to 32.4 °N.

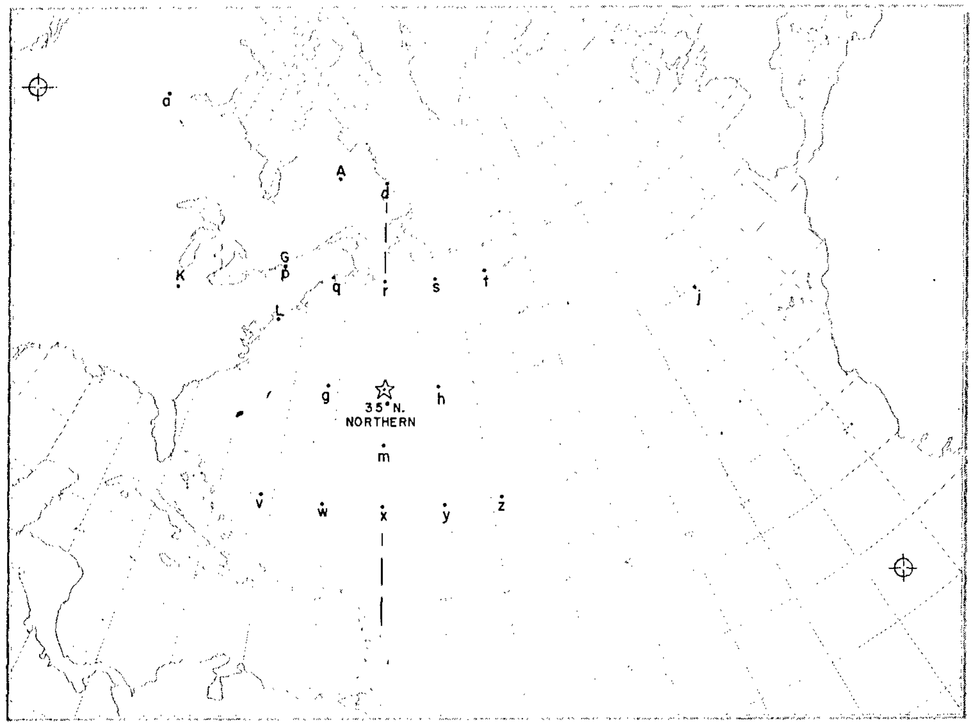

Figure C-5. *Northern Zone Grid Used to Obtain Travelers 24-Hour Hurricane Movement Forecast for Storms Located Between 32.5 °N. to 37.4 °N.*

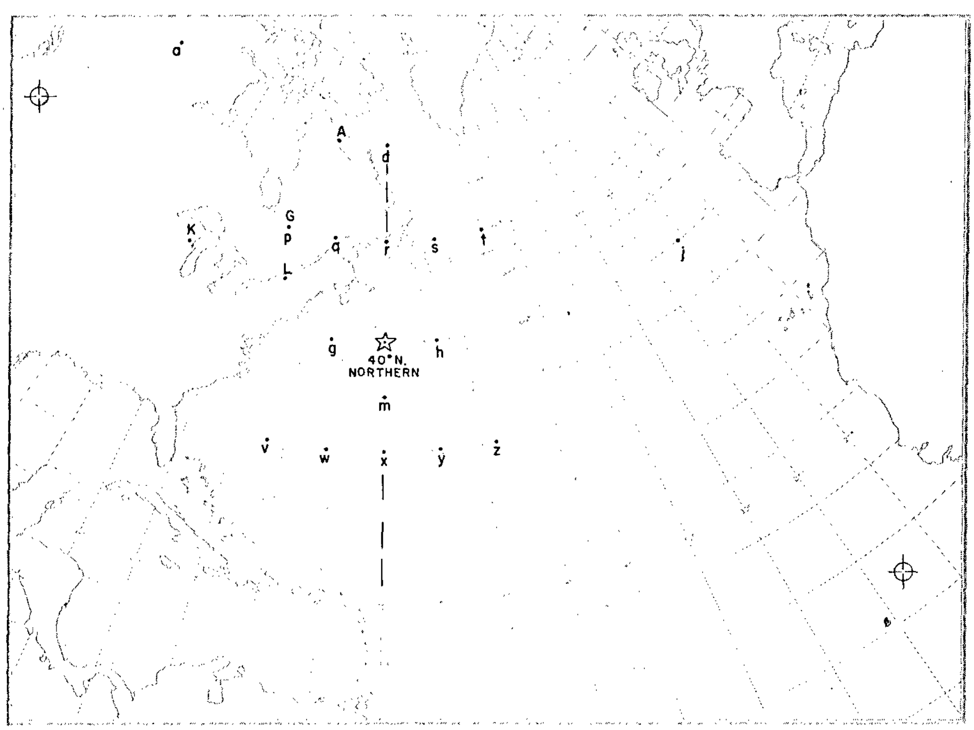

Figure C-6. *Northern Zone Grid Used to Obtain Travelers 24-Hour Hurricane Movement Forecast for Storms Located Between 37.5 °N. to 42.5 °N.*

TABLE C-1. *The Location of Grid Points Needed to Construct the Three Southern Grids (Figures C-1, C-2, and C-3).*

Grid Point	Figure C-1 (15° N.)		Figure C-2 (20° N.)		Figure C-3 (25° N.)	
Southern Grid. Values are in degrees of latitude north or south of the storm center and in degrees longitude east and west of the storm center true when the storm center is at 15° N., 20° N., and 25° N., respectively.						
2	20.0° N.	6.2° E.	20.0° N.	6.5° E.	20.0° N.	7.0° E.
3	15.0° N.	34.8° W.	15.0° N.	36.5° W.	15.0° N.	39.2° W.
7	5.0° N.	0.0° W.	5.0° N.	0.0° W.	5.0° N.	0.0° W.
8	5.0° N.	5.3° E.	5.0° N.	5.5° E.	5.0° N.	5.6° E.
9	5.0° N.	10.7° E.	5.0° N.	11.0° E.	5.0° N.	11.2° E.
10	5.0° N.	16.0° E.	5.0° N.	16.5° E.	5.0° N.	16.8° E.
11	0.0° N.	5.3° W.	0.0° N.	5.5° W.	0.0° N.	5.6° W.
12	5.0° S.	40.8° E.	5.0° S.	41.4° E.	5.0° S.	42.2° E.

movement and a negative value an east movement. The other terms in the equation are similar to those in the equation for latitudinal movement. P_x, in this case, represents the past 12-hour *zonal* movement measured in degrees latitude; if P_x is west then a plus sign is used in the equation and vice-versa.

Detailed procedure for the computation of the longitudinal displacement:

Same as for latitudinal movement except that in step (a) use P_x instead of P_y and in step (g), the answer is the 24-hour longitudinal forecast movement (plus indicates west, minus indicates east).

C.2 Northern Zone Computations

The northern zone computations require sea level pressures, 500-mb. heights, the past 12-hour motion of the storm, and the surface pressure gradient (east-west steering).

C.2.1 Latitude Movement

The equation for the forecast of the 24-hour *latitudinal* displacement $(\Delta\phi)$ of a storm in northern zone is:

$$\Delta\phi = 0.0812 \times (a) + 0.1809 \times (m) + 0.0111 \times (A) + 0.0414 \times (K) - 1.10 - 0.2629 \times (g) - 0.0487 \times (G) \pm 1.0844\, P_y.$$

A positive value for $\Delta\phi$ is (like the southern zone) a forecast of north movement, a negative value indicates south movement. The lower case letters are the sea level pressures in millibars and tenths at the various grid points. The upper case letters are the coded 500-mb. heights at the different grid points (i. e., 19,250 feet is entered 925.0; height values taken from current charts will be in meters and must be converted to feet before entering the computation sheet). The remaining symbols or constants are similar to the southern zone equations.

Detailed procedure for the computation of the latitude displacement (use computation sheet, figure C-8):

Steps (a), (b), (c), and (d) are similar to the southern zone procedure except that in (b), select a northerly grid rather than southerly, and in (c) the center of the grid is denoted by a

TABLE C-2. *The Location of Grid Points Needed to Construct the Three Northern Grids (Figures C-4, C-5, and C-6).*

Northern Grid

All values are in degrees of latitude north or south of the storm center and in degrees longitude east or west of the storm center true when the storm center is at 30° N., 35° N., and 40° N., respectively.

Grid Point	Figure C-4 (30° N.)		Figure C-5 (35° N.)		Figure C-6 (40° N.)	
a	20.0° N.	38.9° W.	20.0° N.	44.0° W.	20.0° N.	51.3° W.
d	20.0° N.	0.0° W.	20.0° N.	0.0° W.	20.0° N.	0.0° W.
g	0.0° N.	5.8° W.	0.0° N.	6.1° W.	0.0° N.	6.5° W
h	0.0° N.	5.8° E.	0.0° N.	6.1° E.	0.0° N.	6.5° E.
j	0.0° N.	34.8° E.	0.0° N.	36.6° E.	0.0° N.	39.2° E.
m	5.0° S.	0.0° W.	5.0° S.	0.0° W.	5.0° S.	0.0° W.
p	10.0° N.	13.4° W.	10.0° N.	14.2° W.	10.0° N.	15.6° W.
q	10.0° N.	6.7° W.	10.0° N.	7.1° W.	10.0° N.	7.8° W.
r	10.0° N.	0.0° W.	10.0° N.	0.0° W.	10.0° N.	0.0° W.
s	10.0° N.	6.7° E.	10.0° N.	7.1° E.	10.0° N.	7.8° E.
t	10.0° N.	13.4° E.	10.0° N.	14.2° E.	10.0° N.	15.6° E.
v	10.0° S.	10.6° W.	10.0° S.	11.0° W.	10.0° S.	11.6° W.
w	10.0° S.	5.3° W.	10.0° S.	5.5° W.	10.0° S.	5.8° W.
x	10.0° S.	0.0° W.	10.0° S.	0.0° W.	10.0° S.	0.0° W.
y	10.0° S.	5.3° E.	10.0° S.	5.5° E.	10.0° S.	5.8° E.
z	10.0° S.	10.6° E.	10.0° S.	11.0° E.	10.0° S.	11.6° E.
A	20.0° N.	7.8° W.	20.0° N.	8.5° W.	20.0° N.	10.6° W.
G	10.0° N.	13.4° W.	10.0° N.	14.2° W.	10.0° N.	15.6° W.
K	5.0° N.	24.4° W.	5.0° N.	26.6° W.	5.0° N.	28.4° W.
L	5.0° N.	12.2° W.	5.0° N.	13.3° W.	5.0° N.	14.2° W.

STORM ________________ MAP TIME ____________

FORECAST VALID TIME ____________

LATITUDE COMPUTATION

Total of Minus Terms			Total of Plus Terms		
(11),	0.0976 × ____ =	________	(3),	0.0841 × ____ =	________
(7),	0.1357 × ____ =	________	(10),	0.1418 × ____ =	________
P_y, (if south)	1.0257 × ____ =	________	P_y, (if north)	1.0327 × ____ =	________
	TOTAL = T_m =	________			+ 7.90

TOTAL = T_p = ________

T_m = – ________

LATITUDE DISPLACEMENT (°LAT.) = $\Delta\phi = T_p - T_m$ = $\boxed{\quad}$

LONGITUDE COMPUTATION

Total of Minus Terms			Total of Plus Terms		
(11),	0.1958 × ____ =	________	(2),	0.0571 × ____ =	________
(12),	0.1730 × ____ =	________	(8),	0.2378 × ____ =	________
P_x, (if east)	1.2873 × ____ =	________	(9),	0.0228 × ____ =	________
	TOTAL = T_m =	________	P_x, (if west)	1.2873 × ____ =	________
					+ 50.60

TOTAL = T_p = ________

T_m = ________

LONGITUDINAL DISPLACEMENT (°LAT.) = $\Delta\phi = T_p - T_m$ = $\boxed{\quad}$

Figure C-7. Computation Sheet for 24-Hour Forecast via Travelers Method on Storms Located at or South of 27.5 °N. (Southerly Grid).

STORM ______________________ *MAP TIME* ______________________

FORECAST VALID TIME ______________________

LATITUDE COMPUTATION

Total of Minus Terms

(g), 0.2629 × ____ = ____________

(G), 0.0487 × ____ = ____________

P_y, 1.0844 × ____ = ____________
(if south)

1.10

TOTAL = T_m = ____________

Total of Plus Terms

(a), 0.0812 × ____ = ____________

(m), 0.1809 × ____ = ____________

(A), 0.0111 × ____ = ____________

(K), 0.0414 × ____ = ____________

P_y, 1.0844 × ____ = ____________
(if north)

TOTAL = T_p = ____________

T_m = − ____________

LATITUDE DISPLACEMENT (°LAT.) = $\Delta\phi = T_p - T_m$ = $\boxed{}$

LONGITUDE COMPUTATION

Total of Minus Terms

(d), 0.0720 × ____ = ____________

(h), 0.1500 × ____ = ____________

P_y, 0.6379 × ____ = ____________
(if south)

P_x, 1.0831 × ____ = ____________
(if east)

S_x, 0.0197 × ____ = ____________
(if minus)

TOTAL = T_m = ____________

Total of Plus Terms

(j), 0.1478 × ____ = ____________

(L), 0.0503 × ____ = ____________

P_y, 0.6379 × ____ = ____________
(if north)

P_x, 1.0831 × ____ = ____________
(if west)

S_x, 0.0197 × ____ = ____________
(if plus)

26.90

TOTAL = T_p = ____________

T_m = − ____________

LONGITUDINAL DISPLACEMENT (°LAT.) = $\Delta\lambda = T_p - T_m$ = $\boxed{}$

Figure C-8. Computation Sheet for 24-Hour Forecast via Travelers Method on Storms Located at or North of 26.0 °N. (Northerly Grid).

star instead of a circle with dot.

(e) Place the center of the grid over the surface position of the storm on the 500-mb. change and align as before.

(f) Read the coded 500-mb. heights for the appropriate grid points (upper case letters located north of grid point) and enter on the computation sheet to the nearest 10 feet (i. e., 19,250 feet, is entered 925.0.)

(g) The 24-hour latitude forecast is now found as was done for the southern zone.

C.2.2 Longitudinal Movement

The equation for the forecast of the 24-hour *longitudinal* displacement $(\Delta\lambda)$ of a storm in the northern zone is:

$$\Delta\lambda = 26.90 + 0.1478 \times (j) + 0.0503 \times (L) - 0.0720 \times (d) - 0.1500 \times (h) \pm 0.6379\, P_y \pm 1.0831\, P_x \pm 0.0197\, S_x$$

The symbols and constants (except for S_x) have been previously defined in either the southern zone or the latitudinal northern zone computations. S_x represents east-west steering due to surface pressure gradients and may be computed using a computation sheet (fig. C-9); if positive, use + sign in equation and vice-versa.

Detailed Procedure:

Steps (a), (b), (c), (d), (e), and (f) are similar to the northern zone latitudinal computation.

(g) Compute east-west steering (see fig. C-9)

1. Enter 5 north grid points (the sea level pressures at *p, q, r, s, and t*) on the computation sheet and add together.
2. Do the same for the 5 south grid points *(v, w, x, y, and z)*.
3. Subtract total south (T_s) from total north (T_n).
4. Find $\frac{1}{\sin\phi}$ for the initial latitude of the storm (use table on computation sheet).
5. Multiply $\frac{1}{\sin\phi}$ by the answer obtained from step 3, the answer to this multiplication is the east-west steering value, S_x.
6. Enter on computation sheet (fig. C-9) for S_x minus or S_x plus depending on the sign of S_x.

(h) The 24-hour longitudinal forecast is now found as was done for the latitudinal computation. Note: the results are in degrees latitude and must be converted to degrees longitude before being added to the present longitude position.

Pressures at North Grid Points	Pressures at South Grid Points
1) p, ______	2) v, ______
q, ______	w, ______
r, ______	x, ______
s, ______	y, ______
t, ______	z, ______
TOTAL = T_n ______	TOTAL = T_s ______

T_n = ______

T_s = ______

3) DIFFERENCE $= T_n - T_s$ = ______

4) STORM LATITUDE = ______°LAT.

$1/\sin\phi$ (from table below) = ______

5) $S_x = \left(\frac{T_n - T_s}{1}\right)\left(\frac{1}{\sin\phi}\right) = \boxed{}$

Storm Lat.	$1/\sin\phi$	Storm Lat.	$1/\sin\phi$	Storm Lat.	$1/\sin\phi$
27	2.20	35	1.74	43	1.47
28	2.13	36	1.70	44	1.44
29	2.06	37	1.66	45	1.41
30	2.00	38	1.62	46	1.39
31	1.94	39	1.59	47	1.37
32	1.89	40	1.56	48	1.35
33	1.83	41	1.52	49	1.33
34	1.79	42	1.49	50	1.31

Figure C-9. Computation Sheet for S_x (East-West Steering) to Be Used in Computing Northern Zone Forecasts.

APPENDIX D

Tropical Cyclone Data Sheets

The storm data used in the report were tabulated on two standard forms; (1) Tropical Cyclone Warning and Verification Sheet (figure D-1) and (2) Objective Forecasting Techniques, Verification and Data Sheet (figure D-2). Included on figures D-1 and D-2 are sample reports which are explained in the following discussion.

D.1 Figure D-1

Column 1. Storm Serial Number (6203) - the year of the storm (1962) and the number of the storm in that year (third storm).

Column 2. Warning Number (08) - the number of the official warning issued on that storm.

Column 3. Warning Date-Time Group (091416) - the time at which the official warning was issued; the ninth month, (September), fourteenth day at 1600 Greenwich Civil Time.

Column 4. Present Position - the latitude (19.6° N.) and longitude (58.2° W.) of the storm at warning time, to the nearest tenth of a degree. This position is the present position as it appears in the official warning.

Column 5. Best Track Position - the latitude (19.5° N.) and longitude (57.8° W.) of the storm at warning time, as determined by post-analysis based on all available data concerning the storm.

Column 6. Present Course (298) - the course that the storm is expected to be on at warning time measured in degrees true.

Column 7. Present Speed (10) - the speed at which the storm is expected to be moving at warning time, measured in knots.

Column 8. Present Intensity (1) - the intensity of the storm as determined by the name of the official warning. Where "0" represents tropical depression intensity (0-34 knots), "1" represents tropical storm intensity (35-64 knots), and "2" represents hurricane intensity (65 knots and greater).

Column 9. Classification (1) - the general circulation pattern influencing the storm course during the forecast period. Where "1" represents tropical easterly steering currents (general movement toward the west, south of a subtropical high cell); "2" represents steering currents attendant to recurvature, poorly defined steering currents and other miscellaneous synoptic situations not defined by "1" or "3"; "3" represents polar westerly steering currents (general movement toward the east.)

Column 10 through 19. Forecast Storm Positions - the position forecast by the methods indicated and for the designated time period. The official forecasts are those given in the official warnings and extrapolation and climatology are defined briefly in the report. FWF 1959 was not used in this study. All positions are recorded to the nearest tenth of a degree.

D.2 Figure D-2

Column 1. Same as on D-1.

Column 2. Synoptic Date-Time Group (091412) - the time of the synoptic chart used to make the objective forecasts; month (09), day (14), and Greenwich Civil Time (1200). The synoptic forecasts on figure D-2 are combined with the official and semiobjective forecasts 4 hours later on figure D-1.

Column 3. Present Position - the latitude and longitude of the storm to the nearest tenth of a degree at synoptic time.

Column 4. Best Track Position - the latitude and longitude of the storm at synoptic time as determined by post analysis.

Column 5 and 6. Same as Columns 8 and 9 on figure D-1.

Column 7 through 17. Forecast Storm Positions - the position forecast by the objective methods indicated and for the designated time period.

The forecast components of movement used in the report were obtained by subtracting the present position of the storm from the final position forecast by the method under consideration, using the data from figure D-1 for the official and semiobjective methods and from figure D-2 for the objective methods. The observed movement was obtained by subtracting the present position at warning time from the best track position 24 hours later from figure D-1 only.

1	2	3	4		5		6	7	8	9	10		11		12		13		14		15		16		17		18		19	
SERIAL NUMBER	WARNING NUMBER	DATE-TIME GROUP (ZULU)	PRESENT POSITION		BEST TRACK POSITION		PRESENT COURSE	PRESENT SPEED	PRESENT INTENSITY	CLASSIFICATION	OFFICIAL FORECAST								EXTRAPOLATION				CLIMATOLOGY				FHFF 1959			
											12 HOUR		24 HOUR		48 HOUR		72 HOUR		12 HOUR		24 HOUR		12 HOUR		24 HOUR		48 HOUR		72 HOUR	
			LAT.	LONG.	LAT.	LONG.					LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.
6203	08	091416	196	582	195	578	298	10	1	1	205	599	218	616	248	648	279	691	202	600	218	619	212	602	227	622				

Figure D-1. Tropical Cyclone Warning and Verification Data Sheet.

1	2	3		4		5	6	7		8		9		10		11		12		13		14		15		16		17	
SERIAL NUMBER	DATE-TIME GROUP (ZULU)	PRESENT POSITION		BEST TRACK POSITION		PRESENT INTENSITY	CLASSIFICATION	TRAVELERS (1960)						MILLER MOORE		AROWA		JOINT NUMERICAL WEATHER PREDICTION											
								12 HOUR		24 HOUR		36 HOUR		24 HOUR		24 HOUR		12 HOUR		24 HOUR		36 HOUR		48 HOUR		60 HOUR		72 HOUR	
		LAT.	LONG.	LAT.	LONG.			LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.
6203	091412	193	574	193	573	1	1	200	588	211	605	233	597	217	602	227	585	193	589	194	610	196	632	200	656	208	681	217	709

Figure D-2. Objective Forecasting Techniques, Verification and Data Sheets.

APPENDIX E

Correlation And Regression Program (CARP)

The program inspects the data and computes the mean, the square of the mean, the variance, and the standard deviation of each predictand (dependent variable) and each predictor (independent variable). Each predictor (forecast movement) is then successively compared with the predictand (observed movement); (1) their mean cross-product, (2) the cross-product of their means, and (3) the correlation coefficient of each predictor with the predictand are all computed and the results are printed out. From the list of correlation coefficients thus created, the program selects that correlation coefficient having the largest absolute value, thereby identifying the predictor which can best predict the observed movement. Using this selected predictor, the program estimates the predictand by means of a regression equation and presents the results in the form

$$Y = AX_1 + B_1 + R_1$$

where Y is the predictand (observed component movement), A_1 and B_1 are constants generated by the program, X_1 is the first predictor, and R_1 is the residual not explained by the rest of the equation.

The residual (R_1) becomes a predictand for a subsequent iteration of the program. The entire process can now be repeated and a search made to find which predictor (forecast) can best predict the residual. The results of the second iteration will be in the form

$$R_1 = A_2X_2 + B_2 + R_2.$$

Similarly, the program can be repeated as many times as desired, either until the variance of the predictand has been reduced to an acceptable value, or until it is evident that no significant benefit can be realized by further computation. When terminated the resulting equations are combined into a single equation of the form

$$Y = A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_5X_5 + B,$$

in which one or more of the coefficients may equal zero.

Note that it is possible, having once selected a given predictor as best correlating with the predictand, to have the program again choose the same predictor on another iteration. However, the same predictor will never be selected on consecutive iterations. If a predictor is selected more than once, the result is simply a modification of the weighting factor or coefficient applied to that predictor and also of the constant, in the equation.

The order in which the predictors were selected by the program for the equations in each group (defined in section 2.5) and the percentage of the variance explained by each selected predictor are given in tables E-1 through E-3.

TABLE E-1. Predictors (with Reduction of Variance) Selected by the Multiple Regression Program for Group I.

	$\Delta\phi$ (Latitude)		$\Delta\lambda$ (Longitude)	
Order of Selection	Predictor	Percent Reduction	Predictor	Percent Reduction
1	Travelers	32.0	AROWA	75.1
2	AROWA	4.3	Travelers	2.3
3	Travelers	1.5	AROWA	1.4
4	Climatology	0.9	Travelers	0.8
5			AROWA	0.6
6			Extrapolation	0.5
Total Percent Reduction		38.7		80.7

TABLE E-2. Predictors (with Reduction of Variance) Selected by the Multiple Regression Program for Group II.

		$\Delta\phi$ (Latitude)		$\Delta\lambda$ (Longitude)	
	Order of Selection	Predictor	Percent Reduction	Predictor	Percent Reduction
Region A	1	Travelers	37.3	Travelers	84.5
	2	AROWA	2.0	AROWA	1.1
	Total Percent Reduction		39.3		85.6
Region B	1	AROWA	34.8	AROWA	70.7
	2	Climatology	9.3	Travelers	3.4
	3	AROWA	0.5	AROWA	2.0
	4			Travelers	1.3
	5			AROWA	0.5
	Total Percent Reduction		44.6		77.9
Region C	1	AROWA	31.7	AROWA	33.5
	2	Travelers	1.8	Travelers	3.7
	3	Climatology	3.8	AROWA	M
	Total Percent Reduction		37.3		38.0*

*Total estimated due to inadvertant termination of iteration prior to typeout of remaining variance.

TABLE E-3. Predictors (with Reduction of Variance) Selected by the Multiple Regression Program for Group III.

		$\Delta\phi$ (Latitude)		$\Delta\lambda$ (Longitude)	
	Order of Selection	Predictor	Percent Reduction	Predictor	Percent Reduction
Set W	1	AROWA	11.0	AROWA	56.5
	2	Travelers	5.8	Climatology	8.5
	3			AROWA	2.9
	4			Climatology	1.5
	Total Percent Reduction		16.8		69.4
Set X	1	AROWA	40.4	AROWA	40.3
	2	Travelers	2.4	Travelers	10.1
	3	AROWA	0.3	Miller-Moore	2.9
	Total Percent Reduction		43.1		53.3
Set Y	1	Travelers	35.7	AROWA	39.4
	2	AROWA	3.8	Travelers	4.4
	3	Travelers	1.5	AROWA	0.3
	Total Percent Reduction		41.0		44.1
Set Z	1	Travelers	33.7	Travelers	72.6
	2	AROWA	3.4	AROWA	1.3
	3			Extrapolation	2.0
	4			AROWA	1.1
	Total Percent Reduction		37.1		77.0

APPENDIX F

Sample Worksheet Form For Solving Regression Equations

Figure F-1 illustrates the general form of the worksheets used to compute the composite forecasts developed in this report. It is possibly more practical to simply solve the equation directly in the case of only one or a few forecasts, but when a great number of forecasts are being made, such as was done in this study, the work sheet method is extremely useful.

The general forms of equations 2.1 through 2.26 are:

$$\Delta\phi = A_1(\Delta\phi)_1 + A_2(\Delta\phi)_2 + A_3(\Delta\phi)_3 + A_4(\Delta\phi)_4 + A_5(\Delta\phi)_5 + C_1$$

for latitude movement, and

$$\Delta\lambda = B_1(\Delta\lambda)_1 + B_2(\Delta\lambda)_2 + B_3(\Delta\lambda)_3 + B_4(\Delta\lambda)_4 + B_5(\Delta\lambda)_5 + C_2$$

for longitude movement. The subscripts correspond to those defined in section 2.5 of the report. In every case certain coefficients (A and B) become zero depending upon the set of equations being used. For example, if equations 2.3 and 2.4 are being solved, A_1, A_2, A_4, B_1, B_2, and B_4 all become zero and A_3, A_5, B_3, B_5, C_1, and and C_2 become 1,072, 0.120, 1.148, 0.140, -0.828, and 0.034, respectively. Then it is merely a question of inserting the proper forecast movement ($\Delta\phi$ or $\Delta\lambda$) in degrees and tenths of degrees *latitude* into the correct space in figure F-1 and carrying out the indicated calculations.

Storm ______________________ *Warning No.* ______________

Forecast Time ______________________ *Verifying Time* ______________

LATITUDE COMPUTATION

Extrapolation Forecast	$(\Delta\phi)_1 \times A_1 =$	______________
Climatology Forecast	$(\Delta\phi)_2 \times A_2 =$	______________
Travelers Forecast	$(\Delta\phi)_3 \times A_3 =$	______________
Miller-Moore Forecast	$(\Delta\phi)_4 \times A_4 =$	______________
AROWA Forecast	$(\Delta\phi)_5 \times A_5 =$	______________
	$C_1 =$	______________
Total = 24-Hour Forecast Movement (Deg. Lat.)	=	______________
Present Latitude	=	______________
24-Hour Forecast Latitude	=	______________

LONGITUDE COMPUTATION

Extrapolation Forecast	$(\Delta\lambda)_1 \times B_1 =$	______________
Climatology Forecast	$(\Delta\lambda)_2 \times B_2 =$	______________
Travelers Forecast	$(\Delta\lambda)_3 \times B_3 =$	______________
Miller-Moore Forecast	$(\Delta\lambda)_4 \times B_4 =$	______________
AROWA Forecast	$(\Delta\lambda)_5 \times B_5 =$	______________
	$C_2 =$	______________
Total = 24-Hour Forecast Movement (Deg. Lat.)	=	______________
Conversion Factor $(1/\cos\phi)$	=	______________
Product = 24-Hour Forecast Movement (Deg. Long.)	=	______________
Present Longitude	=	______________
24-Hour Forecast Longitude	=	______________

Figure F-1. Hurricane Movement Computation Sheet for the 24-Hour Composite Forecast.

Navy Weather Research Facility (NWRF 12-1164-098)
A COMPARISON OF OBJECTIVE HURRICANE FORECASTING METHODS AND ATTEMPTS TO COMBINE TWO OR MORE OF THESE METHODS. November 1964. 62 pp., including 33 figures, 12 tables, and 6 appendices.
UNCLASSIFIED

This report statistically compares the existing forecasting techniques of movement with the official hurricane movement forecast.

Several forecasting methods are combined and various data stratifications are tried in an attempt to improve on the official forecast. The results are encouraging, although not conclusive because of the limited data sample.

1. Meteorology
2. Techniques for Forecasting Hurricane Movement.
   (a) AROWA (Riehl-Haggard) Method
   (b) Miller-Moore Method
   (c) Travelers Method
3. Regression Equations

I. Title: A Comparison of Objective Hurricane Forecasting Methods and Attempts to Combine Two or More of These Methods.
II. NWRF 12-1164-098

TASK 12

UNCLASSIFIED

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